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The Pre-Quaternary history of fire

A.C. Scott *

Department of Geology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK

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Abstract

Although evidence for land vegetation comes from the Silurian, and maybe even earlier, the first record of fossil charcoal (fusain) is from the late Devonian. For this period there are only one or two isolated records. Not until the Early Carboniferous is there a record of extensive charcoal deposits, mainly preserved in near-shore clastic sediments, which provide evidence of significant and widespread wildfires. By the late Carboniferous charcoal was common or abundant in a wide range of facies, including tropical wetland peats. Wildfire played an important role in shaping the environment at this time. The latest Palaeozoic and early Mesozoic records of charcoal are fewer, whereas important deposits of late Mesozoic age are found worldwide. The occurrence of charcoal at the Cretaceous–Tertiary Boundary has been highlighted as evidence for a global fire following a meteorite impact, but this interpretation is questionable. Charcoal has been widely reported from Tertiary sediments and its appearance in the Quaternary and Recent is not solely as a result of human impact. Through the past 400 million years there have been major changes in atmospheric oxygen levels that affected fire intensity and frequency. Fire systems thus have a long history and their impact on shaping the environment is assessed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: charcoal; fire; fossil; fusain; palaeoecology

1. Introduction

Fire is an integral and dramatic part of today's terrestrial world (Pyne, 1995). Every day, somewhere in the world a fire burns. While some of these fires are started by Man, many are truly natural wildfires ignited by lightning strike. Climatic change has now created a general interest in understanding fire (Goldammer and Crutzen, 1993; O'Hanlon, 1995; Woods, 1995; Parfit, 1996; McInnis, 1997). For example, over the past 20 years the El Niño has been considered crucial in leading to conditions for extensive fires in some areas. The fires in Borneo during 1982–83 may have been related to such a short-term climatic change (Johnson, 1984). Equally, small shifts in climate may be seen in terms of fire distribution and intensity (Swetnam and Betancourt, 1990). The effects of fire on the terrestrial world can be devastating, leading to destruction of habitat and increased erosion, but equally may be necessary for the re-growth of specialised vegetation types (Crutzen and Goldammer, 1993; Pyne et al., 1996). The evolution of the latter (Vogl, 1977; Moore, 1978, 1982; Kemp, 1981; Pyne et al., 1996) suggests a long history.

Yet despite the increasing recognition of fire in the fossil record, which is based mainly on the occurrence of fossil charcoal (fusain) (Harris, 1958; Komarek, 1973; Cope and Chaloner, 1985; Scott, 1989; Moore, 1989; Scott and Jones, 1991a), there have been few attempts to investigate its role in

* Tel.: +44-1784-443608. fax: +44-1758-4471780.
E-mail address: a.scott@gl.rhbnc.ac.uk (A.C. Scott)

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the pre-Quaternary terrestrial ecosystem (Scott and Jones, 1994; Falcon-Lang, 2000). Pyne et al. (1996) comment "The conditions that made fire possible on earth appeared approximately 350–400 million years ago. The subsequent history of fire on the planet coincides with the development of terrestrial life, the tectonic breakup of the primordial crust into continents, and the evolution of the atmosphere. Throughout, fire has been a cause, consequence, and catalyst. Its paleohistory, however, is poorly known and little researched." Clark and Robinson (1993) also comment "The many limitations of the fossil record are partly responsible for the sparse attempts to reconstruct fire regimes of the past. Fire ecology over the past 350 million years when fire has been known to exist is almost unstudied, techniques are poorly developed, and interpretations uncertain."

Major problems concern: (1) the lack of awareness of the common occurrence of charcoal in the fossil record; (2) the fidelity of preservation and hence the identification of plants and plant parts; (3) the effect of fires on the Pre-Quaternary terrestrial environment and its inhabitants, including erosion–depositional systems, community development and biological evolution. This paper highlights some of these issues, drawing together both new and published data.

2. Modern fire systems

2.1. Evolution of plants and fire-adapted vegetation

Vascular land plants first spread on to the land in late Silurian times but they apparently did not colonise a wide variety of ecological niches until the Devonian (Taylor and Taylor, 1993). Most of them were small, and it is doubtful whether such communities would have provided enough fuel to sustain a substantial fire.

It is now clear that fires were an important part of Carboniferous terrestrial ecosystems (Scott and Jones, 1994; Falcon-Lang, 2000), but little has been learnt about the effects of regular fires upon plant community structure from most of the fossil record (Clark and Robinson, 1993). Present-day fire-prone communities (Gill et al., 1981) suggest that a considerable period of time, possibly several million years, are needed for adaptation (Kemp, 1981).

2.2. Formation of fuels

Evidence of a build-up of litter as early as the mid-Devonian is shown by thin coals (Han, 1989; Lapo and Druzdova, 1989). However, these are dominated by leaf and stem cuticles and probably were deposited in an aquatic environment and hence may not form a readily available fuel. Large accumulations of plants that formed extensive peats (now coals) are known form the early Carboniferous (Hower et al., 1995). These provide the first evidence for widespread wildfires in the fossil record. The evolution of woody trees and the spread of extensive forests in the late Devonian at this time raise the possibility of increased quantity of fuel augmented by the development of megaphyllous leaves (Collinson and Scott, 1987). Robinson (1989, 1991) argued that litter build-up would have been greater in the Palaeozoic and early Mesozoic because of the absence of basidiomycetes capable of degrading lignin at this time. There is no evidence, as Clark and Robinson (1993) have suggested, that Carboniferous arborescent lycopods were fire resistant. Indeed the opposite was probably true (Falcon-Lang, 1999c).

Some late Palaeozoic plants were probably deciduous (such as the Permian *Glossopteris*), leading to extensive accumulations of surface rotting litter. This would have easily burnt. By the late Devonian probably, and certainly by the Carboniferous, fuels accumulated in the form of crown vegetation, surface litter and organic soil debris, such as peat or duff. This could have acted as a fuel for fire (Davis, 1959, Fig. 1). Research on fuel type, condition and build-up is essential for understanding the types of fire (Albini, 1993; Pyne et al., 1996, Fig. 2).

2.3. Ignition

There are four major ways (apart from human intervention) by which fires may be ignited: lightning strike, volcanic activity, sparks from rock falls and spontaneous combustion (Batchelder, 1967). Meteorite impact has also been cited [see

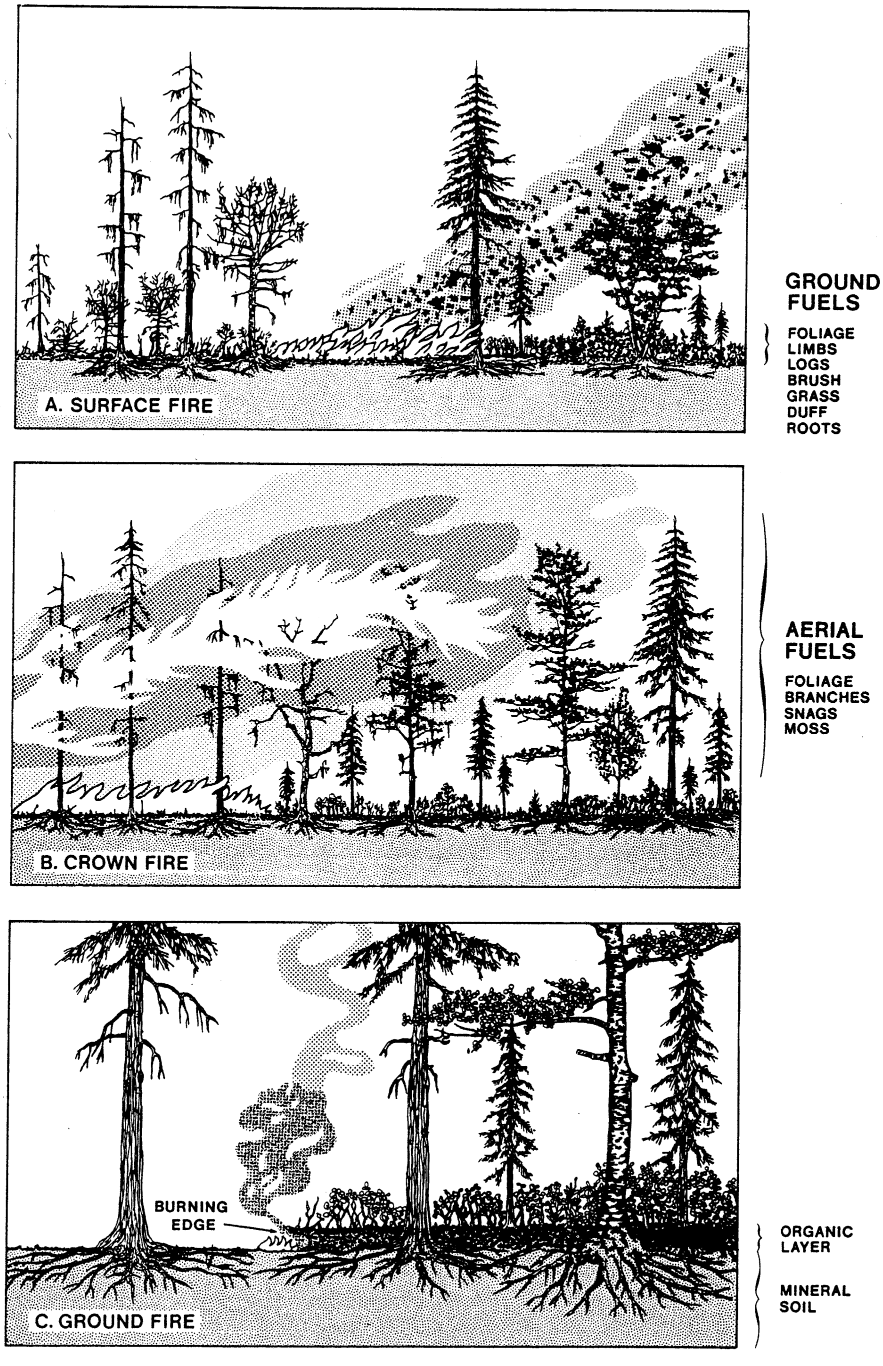


Fig. 1. Types of wildfire and sources of fuel [from Scott (1989) modified from Davis (1959)].

Jones and Lim (2000)]. By far the most important today is lightning strike (Komarek, 1967). Komarak (1967) showed that in North America there are over 5000 fires in the US National Forest alone started each year by lightning. Pyne et al. (1996) calculated that each day there are well over

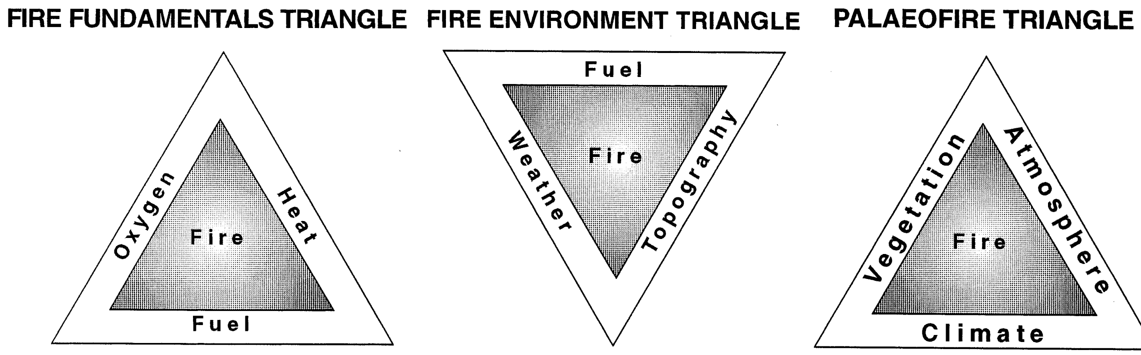


Fig. 2. Fire triangles showing the fundamentals of fire [after Pyne et al. (1996)], the fundamentals of a fire environment [after Pyne et al. (1996)] and of palaeofire.

eight million strikes worldwide. Not all lightning strikes result in fires. Today, lightning fires contribute up to 10% of global biomass burning (Crutzen and Andrae, 1990; Lobert and Warnatz, 1993). In the past, before human influence, lightning strikes were almost certainly the main cause of fire. Modern lightning fires occur in a wide range of vegetation types, including deciduous and semi-deciduous forest biomes and occasionally in rain forest (Goldammer, 1993).

For a fire to start and spread there needs to be four phases of combustion: pre-ignition, ignition, combustion and extinction (Pyne et al., 1996). In the pre-ignition phase the temperature of the fuel is raised by endothermic reactions so that water evaporates and volatiles are released (Pyne et al., 1996). The volatile gases are combustible and produced by pyrolysis and volatilisation of a number of organic compounds, including plant waxes and oils. Dehydration can be rapid and the pyrolysis also generates tars and other liquid products and carbonaceous char and ash. The temperatures reached may greatly affect the relative proportions of these products: low temperatures produce higher char and tar yields and higher temperatures generate higher yields of volatiles, which are flammable (Pyne et al., 1996). Polycyclic aromatic hydrocarbons (PAHs), may also be produced, and these are useful as geochemical markers for fire in fossil sediments (Zepp and Macko, 1997).

The thermal degradation of different plant compounds changes with temperature and may affect the physical and chemical nature of the remaining char. Cellulose (70% of wood cell walls) is stable up to 250°C and at 325°C begins to break down, generating flammable gases. In contrast, lignin (comprising 30% of wood cell walls) is more resistant to thermal degradation and is more prone to survive as a char product (Pyne et al., 1996).

Ignition is regarded as a transition from the pre-ignition state, described above, to combustion and produces a strong exothermic reaction, which must take place for an extended period for combustion to occur and spread. Temperatures for this to happen are around 325°C (Pyne et al., 1996). Although lightning strikes are a major cause of ignition, spontaneous combustion can also occur. This may happen if accumulated plant litter generates heat internally by exothermic processes faster than it is lost to the atmosphere. Microbial activity may first increase the temperature to around 70°C, but then chemical oxidation takes place, which may be aided by moisture, and ignition may follow. In all cases a good supply of oxygen is required.

Two forms of combustion are commonly recognised, flaming and smouldering, the proportion of each changing through the life of a fire. Oxygen is essential for the reactions and fire to continue. Flames are produced by the gases produced and depend on the amount and nature of volatile compounds. Flames are produced over 425–480°C, but the maximum temperature reached may be 1900–2200°C under laboratory conditions. Temperatures over 1650°C have rarely been

reported (Pyne et al., 1996). Common flame temperatures in fires are 700–980°C.

Smouldering or glowing combustion is also important in wildfire situations. As pointed out by Pyne et al. (1996) "surface fires frequently ignite smouldering ground fires". Within litter layers the temperatures are often lower, around 300°C, but elsewhere may reach 600°C and remain high for several hours (Pyne et al., 1996). Such a mechanism may therefore give rise to large quantities of charcoal.

Extinction of a fire occurs when the fuel is exhausted or the heat is reduced. The moisture content of a fuel exerts a major effect on the mode of extinction of a fire.

2.4. Combustion products

The products resulting from wildfire may be considered as a solid residues or gases (Novakov et al., 1997). Solid and gaseous residues may combine to form smoke; large quantities may cause major environmental damage in both the short term (such as the smoke haze across southeast Asia in 1998) and long term with the build up of greenhouse gases and their atmospheric effects (Pyne et al., 1996), although these effects may be partly reversed as the sites regrow. In this paper I am concerned mainly with the solid particulate residues. Some of these residues in smoke are formed by the agglomeration of condensed hydrocarbons and tars and include soot or black or elemental carbon (Jones et al., 1997). Small wind-borne particles will also include charcoal (Komarek et al., 1973), and many particles will be less than 2.5 μm (Griffin and Goldberg, 1979).

Larger combustion residues comprise charcoal: charcoalified and partially charred plants, all of which have potential for being incorporated into the fossil record. Komarek (1973) has pointed out that the charring of wood, for example, decreases its susceptibility to decay, hence increasing its preservation potential (Scott, 1989, 2000).

This paper is concerned with the history of fire in the pre-Quaternary, before the advent of major anthropogenic fire, and considers the nature and effects of fires based mainly on the macroscopic charcoal record.

2.5. Fire classification

Fires may burn fuel from various sources: from living plants, from recently dead plants or from decayed plant accumulations. Many fires may burn only recently dead litter accumulations. Fires of this type are known as surface fires and may also affect living shrubby and herbaceous plants along with the litter (Fig. 3). Such fires are of low temperature (<350°C) and produce the largest quantity of charcoal (Albini, 1993; Stocks and Kauffman, 1997).

Fire may spread into the crowns of trees. These predominantly burn living plant material and tend to be hotter (Fig. 1; Pyne et al., 1996). Crown fires are often ignited by surface fires (Van Wagner, 1977) and often burn only the twigs and needles (Stocks and Kauffman, 1997). If there is extensive soil humus or peat accumulation a ground fire may result (Fig. 1) and this decaying vegetation may burn. Such fires may be of low temperature (<350°C) but last for hours, days or, in some cases, years.

Fire temperatures also may vary between different vegetation types (Rundel, 1981) and some communities are more prone to surface rather than crown fires (Pyne et al., 1996). Fires often burn in a mozaic pattern, helping the vegetation to recover (Monastersky, 1988).

Fire intensity may also reflect fuel load. It is possible for intense fires to occur in environments not prone to fire where there has been an extensive build up of fuel. In such settings a fire would be catastrophic (Batchelder, 1967; Monastersky, 1990).

Documentation of fire regimes may incorporate data on fire history — particularly on fire frequency or fire return intervals — as well as other data on the ecosystems concerned. There have been several classifications of fire regimes. Heinselman (1981) developed the following classification of fire regimes in North America.

Class 0: no natural fire;
Class 1: infrequent, light surface fires (more than 25 year return interval);
Class 2: frequent, light surface fires (1–25 year return intervals);

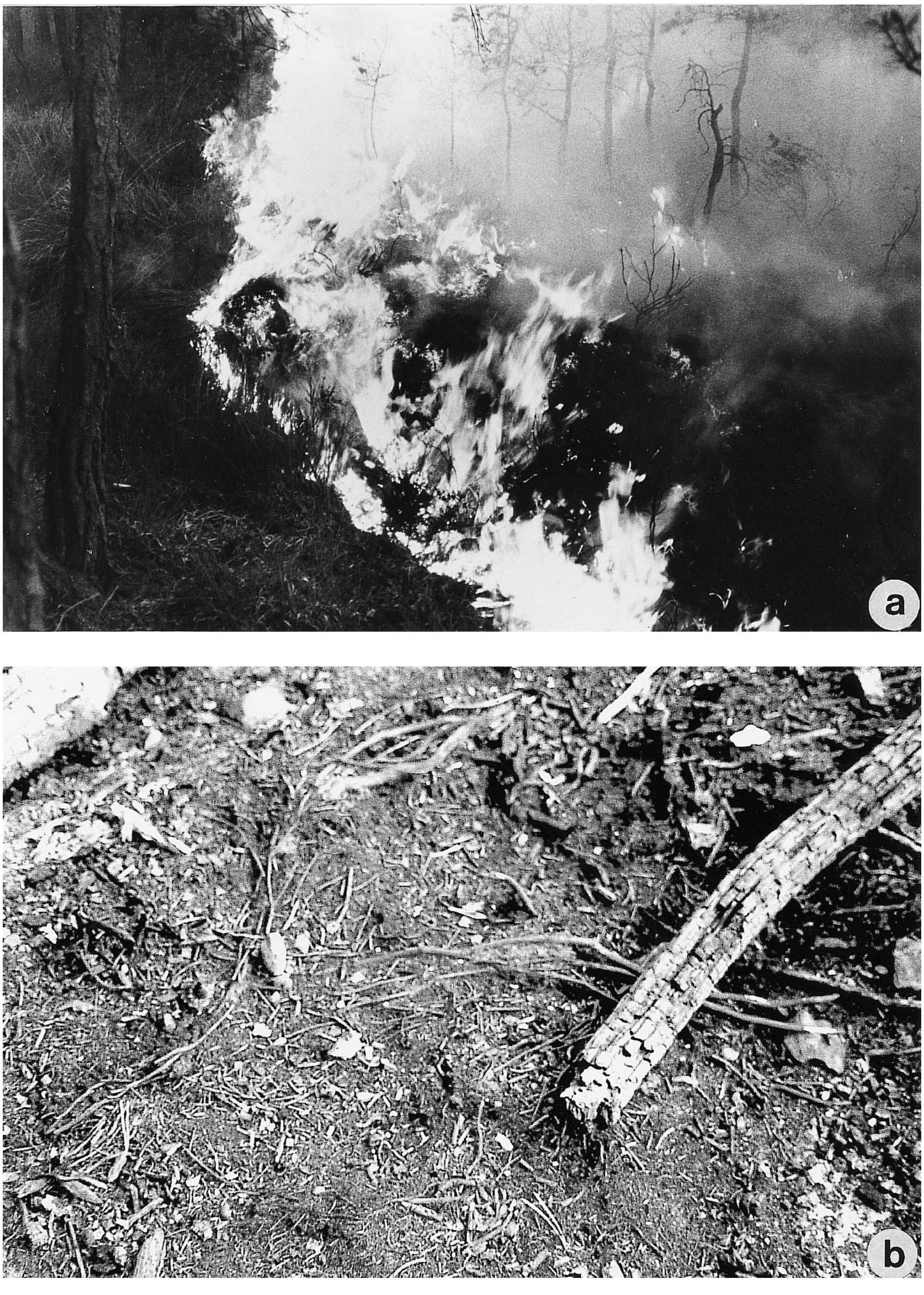


Fig. 3. (a) Recent surface fire, Thursley, Surrey, England, 1991 [see Scott and Jones (1994)] NGR SU49051415. (b) Charcoal produced after recent surface fire, Frensham, Surrey, 1995, photograph 20 cm across [see Scott et al. (2000a)] NGR SU48681400.

Class 3: infrequent, severe surface fires (more than 25 year return intervals);
Class 4: short return interval crown fires and severe surface fires in combination (25 to 100 year return intervals);
Class 5: long return interval crown fires and severe surface fires in combination (100 to 300 year return intervals);
Class 6: very long return interval crown fires and severe surface fires in combination (over 300 year return intervals).

Other schemes have broadened this classification (Pyne et al., 1996), but all include consideration of fire type and fire return interval, and in some cases ecosystem data. There has been little attempt to apply this approach to pre-Quaternary fire systems.

2.6. *Effects of fire*

Fire may or may not destroy a plant community. It may affect not only the plant community but also associated animals, the soil and water chemistry and hence the erosion–depositional system (Swanson, 1981; Pyne et al., 1996).

Some plants (e.g. *Ulex*) need fire for seed germination. The heat of the fire is enough to crack the seed coat and releases many seeds to germinate (Pyne et al., 1996). Some trees, notably some conifers, have fire-resistant bark that protects the vulnerable cambium. These may shed their lower branches, thus reducing the risk of surface fires turning into crown fires. Some plants (e.g. *Eucalyptus*, *Sequoia*, *Betula*) may regenerate or produce new shoots from burnt trunks.

The burning of plants releases nutrients into the soil and dramatically affects its structure (Cerida et al., 1995). Plant communities can simply regenerate in situ or their destruction can lead to a new plant succession (Kozlowski and Ahlgren, 1974; Walker, 1982). Animals are also affected indirectly by killing or disruption of habitat (Pyne et al., 1996).

Influences on the soil depend critically on the nature of the fire: intensity, frequency and timing (Pyne et al., 1996). In particular, the organic-rich layer may be destroyed and the death of the binding roots lead to substantial soil erosion (Swanson, 1981). Soil permeability may also be affected, but this is variable. Several papers deal with the subject (St. John and Rundel, 1976; Sala and Rubio, 1994; Cerida et al., 1995), but few geologists have considered them in their erosion–depositional models.

Rollins et al. (1993) investigated the effects of fires on the chemical and petrographic composition of peat in the Snuggedy Swamp, USA. They demonstrated that some fires were sufficiently intense to burn the peat. However, they also showed that these burns were not sufficient to alter the vegetation. However, fires in mire systems can dramatically alter the hydrologic system. Thus Cohen (1974) showed that peat fires may lower the topography of the peat, leading to flooding and the arrival of sediment via stream crevassing, producing a ‘fire splay’. In some cases the position of the peat surface and water table are sufficiently altered in mire systems for lakes to form (Cypert, 1973). Fire can also initiate mire formation by altering soil permeability.

3. Recognition of fire in the pre-Quaternary fossil record

3.1. *Fusain as fossil charcoal*

Fusain is one of the four lithotypes of coal that were described by Stopes (1919). It was then variously known as ‘Mother of Charcoal’, ‘mineral charcoal’, ‘faserkohle’, etc. [see Scott (1989)]. The term fusain was first introduced by Grand ’Eury (1882) to describe black, silky, lustrous bands macroscopically recognisable in coal (Jones et al., 1997). Its definition was formalised by the International Committee for Coal Petrology (1963), based upon physical (generally optical) and chemical properties rather than mode of origin. For this reason ‘fusain’ has been used rather than ‘charcoal’ in descriptions of fossil material. Until recently, some authors have doubted its identification as fossil charcoal (Schopf, 1975). For example: “it is quite impossible for me to conceive of fusain as exclusively the result of forest fires” [White in Stützer (1929)] and “For some and probably for the majority of the occurrences

of fusain the forest fire origin seems ruled out" (Schopf, 1975).

Over the past 15 years the identity of fusain as fossil charcoal has been proved beyond doubt (Cope, 1980, 1981, 1984; Scott, 1989, 2000; Jones, 1993).

3.2. Macroscopic appearance

Fusain has been defined as wedges and patches of fibrous black and opaque material showing the cellular structure of wood with the cell lumina being generally empty (Stopes, 1919). Later descriptions incorporate the idea that fusain occurs in bands within coals > 37 mm thick (International Committee for Coal Petrology, 1963; Jones et al., 1997). The problem of these definitions is that fusain is conceived as two 'materials': fusain derived from wood and fusain derived from other plant tissues or organs for which there is no formal description. For instance, can small leaves occurring in shale, but bearing many of the same physical and chemical characteristics of fusain derived from wood occurring in coal, also be called fusain?

Macroscopically, fusain fragments derived from wood are characteristically cuboid in shape (Fig. 4b). The material has a black silky lustre, is friable and easily blackens other objects on contact. Microscopically its structure is cellular. In all physical aspects fusain is identical with wood charcoal (Fig. 4a).

Clearly, many different plant parts may be preserved in a similar manner leaves (e.g. Alvin, 1974; Scott and Chaloner, 1983), flowers (e.g. Friis and Skarby, 1981, 1982) and sporangia (Scott et al., 1986; Scott, 2000). Large accumulations of cuboid fragments of fusain are easily recognised

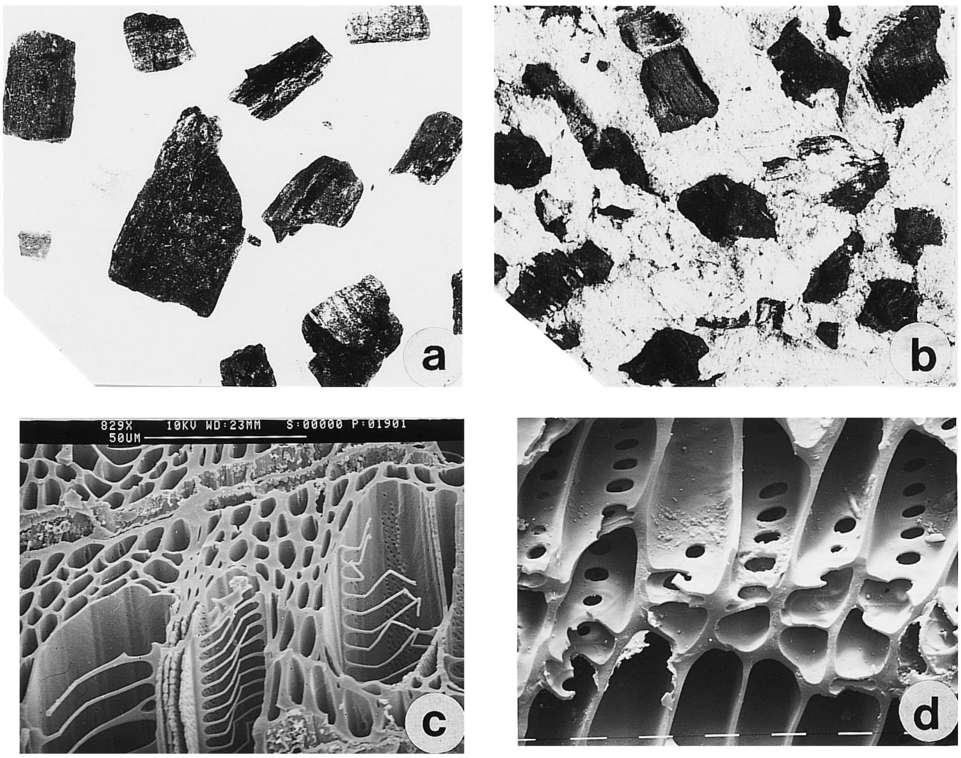


Fig. 4. Recent charcoal and fossil fusain. (a) Recent charcoal of beech (*Betula*) (×1). (b) Fossil conifer charcoal (fusain), from the Jurassic of Yorkshire (×1) NGR TA030940. (c) Scanning electron micrograph of Recent beech charcoal (scale bar 50 μm) seen in (a). (d) Scanning electron micrograph of Jurassic fusain (scale bar 10 μm) seen in (b).

in ancient sediments, but smaller organs of different shapes are easily missed. Thus, while in some cases (e.g. in the Wealden of Southern England) fern pinnules preserved as fusain are readily recognised (Harris, 1981), the smaller leaves may only be recovered by bulk maceration (Harris, 1957; Scott and Collinson, 1978). Probably, therefore, a wide range of material preserved as fusain is missed because bulk maceration has not been undertaken.

This paper deals with only the larger isolated fragments of fusain that are generally accepted as fossil charcoal and will be referred to as such.

3.3. Microscopic appearance

Under a simple hand lens it is usually possible to recognise anatomical features in fusain. Coal petrologists have generally studied it on polished blocks in reflected light under oil (Fig. 5). The term maceral is given to a microscopically recognisable individual constituent of organic matter (Stopes, 1935; Taylor et al., 1998). As macerals are defined by microscopic characteristics their linkage to a lithotype or plant tissue is always partly problematic. Fusain comprises the macerals 'fusinite' and 'semifusinite' (Fig. 5). Fusinite is defined by the International Committee for Coal Petrology (1975) as having highly reflecting cell walls. Open cell structure is often present and 'bogen-structure' is common (i.e. where cell walls have been shattered into angular fragments). In reflected light under oil the cell walls often appear white, showing high reflectance independent of rank. Reflectance ranges quoted are not normally given precisely, but Jones et al. (1997) suggest a minimum of 2.0% Ro. Semifusinite is used for materials ranging between vitrinite and fusinite and show intermediate reflectances (International Committee for Coal Petrology, 1975). Cell walls are generally thicker and cell lumina may be partially closed. Reflectance colour is generally grey to white and reflectance is generally less than 2% Ro (Jones et al., 1997).

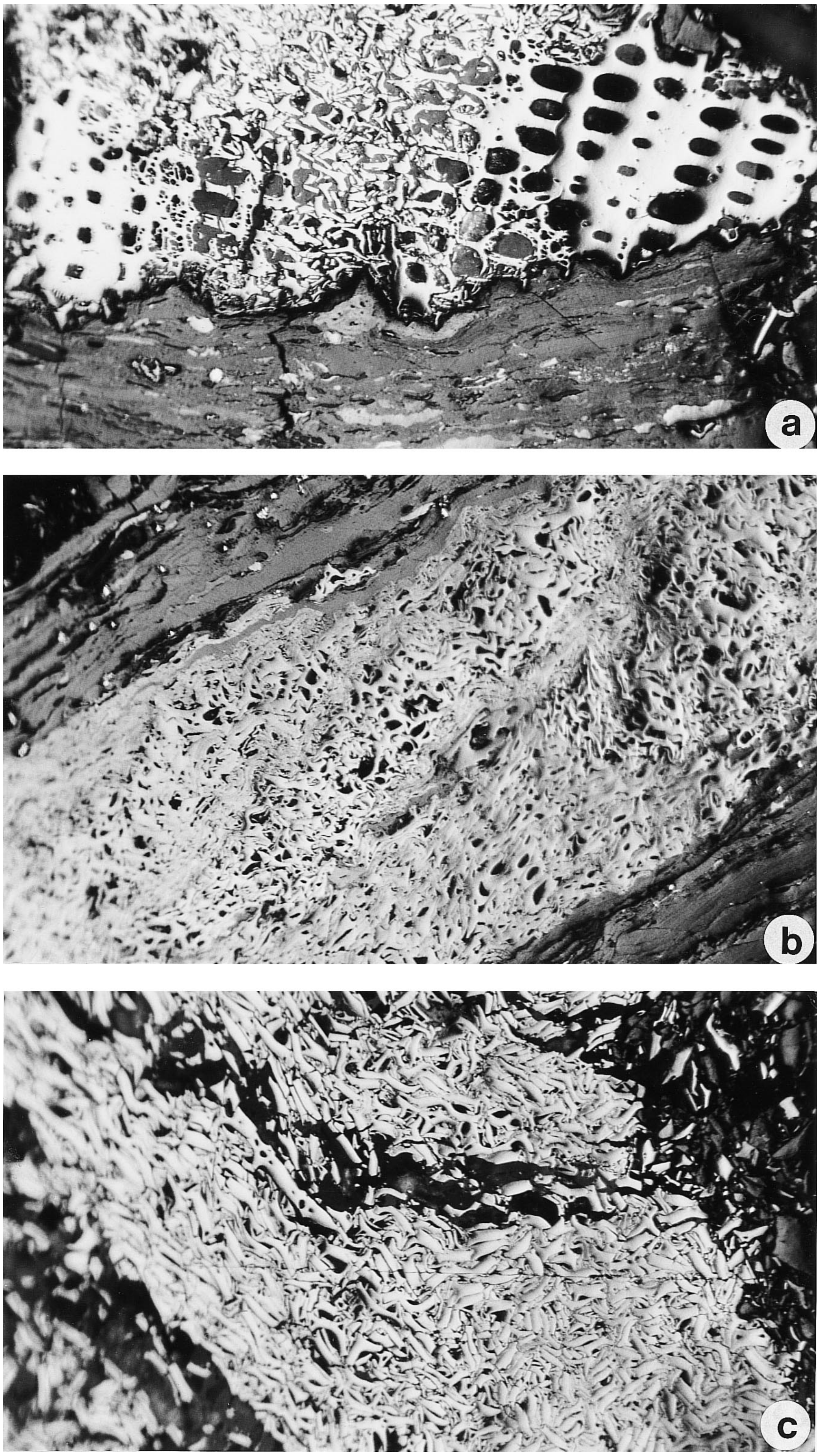
Over recent years it has become established practice, however, to classify fusinites into four categories according to their interpreted origin: pyrofusinite being related to a fire origin; degradofusinite (also oxyfusinite) to oxidation and bacterial decay; rank fusinite to processes taking place during geochemical coalification; and primary fusinite thought to originate in living plant cell walls [see Taylor et al. (1998) and Jones et al. (1997) for a discussion]. This classification has been debated (Winston, 1993; Jones et al., 1997; Scott et al., 2000a). The term 'inertodetrinite' has been introduced to cover 'redeposited' debris of the inertinite group macerals such as fusinite, semifusinite, sclerotinite and macrinite (Taylor et al., 1998).

Charcoal cannot be distinguished from fusain microscopically (Fig. 6). In reflected light it shows open cell structure, brittle cell walls and high reflectance (Scott, 1989). Depending on fire temperature, it may be described as fusinite or semifusinite according to reflectance (Jones et. al., 1991, 1993; Scott and Jones, 1991b, 1994; Guo and Bustin, 1998). Small microscopic charcoal particles are described petrographically as inertodetrinite.

3.4. Chemistry

Significant chemical changes take place in plant material during the charring process (Jones, 1993). Most research has considered the changes in wood chemistry during the charring process. Cope (1980, 1981), Jones et al. (1997) and many others have shown there to be a distinct elemental change with the increase of carbon relative to other common elements, H, O and N, with increasing temperature. This relates to an overall loss in mass, which accounts for a loss in volume (Prior and Gasson, 1993; Lupia, 1995). Breakdown of cellulose followed by alteration of lignin can be demonstrated by a range of techniques such as solid state nuclear magnetic resonance (NMR; Jones, 1993), Fourier transform infrared spectroscopy (FTIR; Guo and Bustin, 1998; Bustin and Guo, 1999) and electron-spin resonance (Austen et al., 1966; Cope, 1980). The changes that occur during the rise in temperature appear to take place abruptly in relation to the breaking of particular chemical bonds and changes in functional group chemistry (Bustin and Guo, 1999).

When charred, most plants retain their characteristic isotopic signature, although this is not always the case (Jones, 1994).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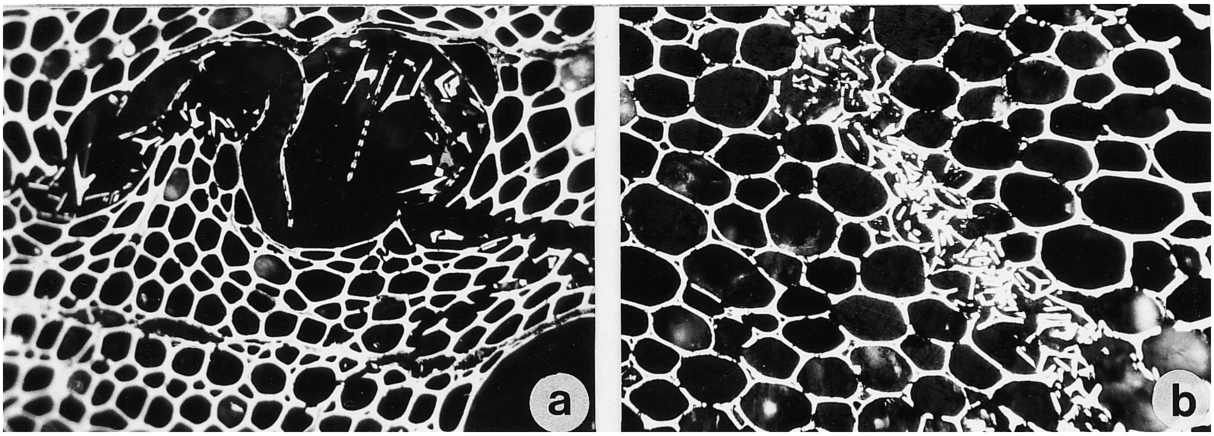


Fig. 6. Reflectance micrographs of recent and fossil charcoal (fusain). (a) Reflectance micrograph of recent beech charcoal (see Fig. 4a) (×40). (b) Reflectance micrograph of Jurassic charcoal (fusain) (see Fig. 4b) (×30).

3.5. Facies distribution of macro- and micro-charcoal

Microscopic charcoal may be wind blown and larger macroscopic fragments are more likely to be water borne. Stocks and Kauffman (1997) comment that high-intensity wildfires are likely to be responsible for most of lake-sediment charcoal. Surface fires appear to result in large amounts of charcoal (Stocks and Kauffman, 1997), most of which stays on site rather than being transported by convective processes (Stocks and Kauffman, 1997). Such material is likely to be water transported at some stage.

One result of the formation of distinctive size categories of charcoal and different transport processes is that evidence for a fire may spread well beyond the area affected by the fire (Clark, 1988). The distribution of fine charcoal particles in peats and lake sediments has been widely used to interpret Quaternary (Patterson et al., 1987; Edwards and Whittington, 2000) and Recent fire history (Earle et al., 1996; Sarmaja-Korjonen, 1998), yet studies of pre-Quaternary fire history have relied principally on macroscopic charcoal (Scott, 1989; Scott and Jones, 1991a, 1994).

It has been widely assumed that in lake sediments the microscopic charcoal records regional fires, whereas macroscopic charcoal records local fires (Clark and Patterson, 1997). Although this is possible, it must be noted that larger fragments take longer to sink than smaller and may be transported further from the site if the material is moved by water (Nichols et al., 2000). This would explain the relative abundance of fossil charcoal in estuarine and near-shore marine sediments (Nichols and Jones, 1992; Falcon-Lang, 1998).

Charcoal is found in a very wide range of facies, from peats (Cohen et al., 1987; Rollins et al., 1993) to lake sediments (Millspaugh and Whitlock, 1995), alluvial fan deposits (Meyer et al., 1992), fluvial and floodplain deposits and marine sediments (Bird, 1997; Wang et al., 1999). Deeper marine sediments yield very small particles, most of which were probably wind blown from very large fires (Smith et al., 1973; Suman et al., 1997) and these have been used to interpret regional fire history (Herring, 1985; Wang et al., 1999).

3.6. Evidence from lightning strikes

In general it is difficult to see the effects of lightning strikes. Sometimes they leave a scorch

Fig. 5. Inertinites from Carboniferous coals. (a) Fusinite showing bogen-structure from a Carboniferous coal, Poland (×100). (b) Fusinite and semifusinite from a Carboniferous coal, Poland (×100). (c) Fusinite and inertodetrinite from a Carboniferous coal, Poland (×100).

mark on a tree, but most hit the ground. The high temperature may fuse minerals, especially sand grains, in the soil or rocks to form fulgarites. Fulgarites have been rarely reported in the fossil record, but they are known in sediments as old as the Permian (Harland and Hacker, 1966).

3.7. Evidence from fire scars

Fires may pass through a wood or forest and while burning or charring the outer bark or trunk may not kill the tree (Ahlgren, 1974; Pyne et al., 1996). In such cases the growth may be interrupted but not halted, and the resulting scars can be seen in transverse sections of the trunk. Fire scar data have been used to date more recent fires (Agee, 1990; Millspaugh and Whitlock, 1995) and may be manifested as traumatic growth rings.

Although analysis of fire scars has commonly been applied to more recent fire systems, it has rarely been used or even noted in ancient woods. Dechamps (1984) reported fire scars in several late Tertiary woods from North Africa. Older woods with fire scars have been reported in Triassic wood from Antarctica (Putz and Taylor, 1996) but are so far unconfirmed.

4. Methods for the study of fossil charcoal

Several recent papers describe methods of studying modern and fossil charcoal (Scott, 1989, 2000; Sander and Gee, 1990; Figueiral, 1999; Nichols, 1999) and only a few aspects are highlighted here.

4.1. Scanning electron microscopy

Fossil charcoal has long been known to preserve excellent anatomical structure (Lyell, 1847; Scott, 1998). The scanning electron microscope (SEM) reveals anatomical preservation to its best advantage (Muir, 1970). Seminal papers by McGinnes et al. (1971, 1974) demonstrated the use of the SEM in charcoal research. Most studies on macroscopic fossil charcoal now employ the SEM (e.g. Alvin, 1974; Scott, 1974; Scott and Collinson, 1978; Friis, 1985a,b,c; Herendeen et al., 1994; 1995; 1999). Those on microscopic charcoal utilise palynological light-microscopic preparations (Clark, 1988), and rarely thin sections (Clark and Patterson, 1997) or bulk geochemical techniques (Bird, 1997).

4.2. Reflectance microscopy

Fossil charcoal was first recognised from coal deposits (Scott, 1989), where it was termed fusain. Coals are generally studied by reflectance microscopy of polished blocks under oil (Taylor et al., 1998). Coal petrologists recognise fundamental particles called macerals (Teichmüller, 1989), which include ‘inertinites’ encompassing fusinite and semifusinite. These are now widely believed to represent fossil charcoal (Scott, 1989; Guo and Bustin, 1998).

Fusinite and semifusinite are identified not only by anatomical features, but also their high reflectance, a characteristic of recent charcoal (Scott, 1989; Scott and Jones, 1991b). Proportions of fusinite and semifusinite vary among coals (Robinson et al., 1997) and may have significance in interpreting fire types or atmospheric history.

4.3. Taphonomy: studies of modern fires; wind and water transport

Much attention has been paid to the wind transport of small charcoal particles (Clark, 1988). Such particles may be transported considerable distances from the site of a fire (Clark, 1988) and reach oceanic sediments (Herring, 1985). Some aspects of microscopic charcoal transport are reviewed by Edwards and Whittington (2000).

Less attention has been paid to the dispersal of macroscopic charcoal particles by water. Studies in Yellowstone Park, USA (Meyer et al., 1992; Whitlock and Millspaugh, 1996) indicate that they are incorporated into alluvial fan and lake sediments. It is also clear that particles may be reworked (Bradbury, 1996). Modern taphonomic work on the water transport and deposition of larger charcoal fragments is required.

4.4. Charring experiments

Inertinite group macerals show high reflectance under oil (Taylor et al., 1998). Fusinites may show reflectances over 6%. It is clear that these are

gained before the material is incorporated into the sediment or peat. It has been widely recognised that charcoal also shows high reflectance and that this is the result of heating by fire (Scott, 1989; Teichmüller, 1989; Taylor et al., 1998). It seemed likely that increasing charring temperature should yield increasing reflectances. Scott (1976, 1989) undertook a series of charring experiments to investigate temperature versus reflectance for experimentally charred plants (1973–1976). This research was continued by Cope (1993) and Jones (1991). A range of charring experiments by Scott, Cope and Jones established the relationship between increasing temperature and reflectance under oil for a range of modern woods (Jones et al., 1991; Scott and Jones, 1991b) (Fig. 7). Increasing reflectance was seen only in woods charred at 200°C for over 1 h. At about 300°C reflectances increased to over 1% and at 400°C to up to 2%. Most reflectances over 2% were reached above 500°C. Temperatures above 900°C were needed for reflectances over 6%.

Independently, Correia et al. (1974) published experimental data where woods were charred in the range 250–700°C. They also found reflectance increasing with temperature, viz.: 0.6% at 300°C, 1.02% at 375°C; 2.05 at 500°C and 4.4% at 700°C. These results are very compatible with those of Scott and colleagues (Scott and Jones, 1991b; Jones et al., 1991; Fig. 7).

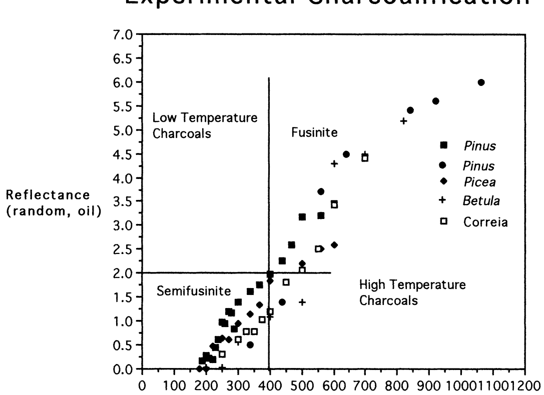


Fig. 7. Reflectance of experimentally produced charcoal showing increasing reflectance with temperature. All samples were charred in the absence of air for 1 h. [Data from Scott and Jones (1991b), Jones et al. (1991) and Correia et al. (1974).]

Further experimental data have been published by Guo and Bustin (1998) and Bustin and Guo (1999). These workers followed the experimental techniques of Jones et al. (1991) and generally confirmed their results. In addition to heating samples in the absence of air for 1 h, Guo and Bustin (1998) varied the heating time from 6 to 240 min and used fresh as well as fungally decayed wood. They demonstrated that the rate of increase in reflectance is strongly temperature dependent. However, at temperatures below 350°C the maximum reflectance stabilised within 1 h and reached a reflectance of 1% at 320°C. In contrast, above 450°C there was a rapid rise of reflectance with time. At 600°C a reflectance of 5% was reached within 30 min.

In addition to fresh woods, Guo and Bustin (1998) experimented with fungally decayed woods. They noted that these required lower charring temperature and heating duration than fresh woods to achieve a specific reflectivity. This was attributed to an increase in the surface area of the tissue enhancing the susceptibility to charring. One overall conclusion was that charcoals with reflectances greater than 2% (i.e. fusinites sensu Jones et al., 1997) form only at temperatures higher than 400°C, regardless of heating duration (Guo and Bustin, 1998).

4.4.1. Morphology

Distinctive morphological changes also occur during charcoalification. Numerous studies of charcoals have been made using scanning and transmission electron microscopy. Wood cell walls show a distinctive layered structure with a primary and secondary wall with a middle lamella. The middle lamella is seen in woods that have been charred below 300°C (Fig. 8a). Homogenisation of the cell wall was first noted by McGinnes et al. (1971). Cope (1980, 1981) and Jones and co-workers (Jones et al. 1991; Scott and Jones, 1991a,b; Jones, 1993) noted that the degree of homogenisation of the cell wall varied between 280 and 320°C depending on the taxon (Fig. 8b). Scott and Jones (1991b) investigated the changes in the cell walls of wood by both reflectance

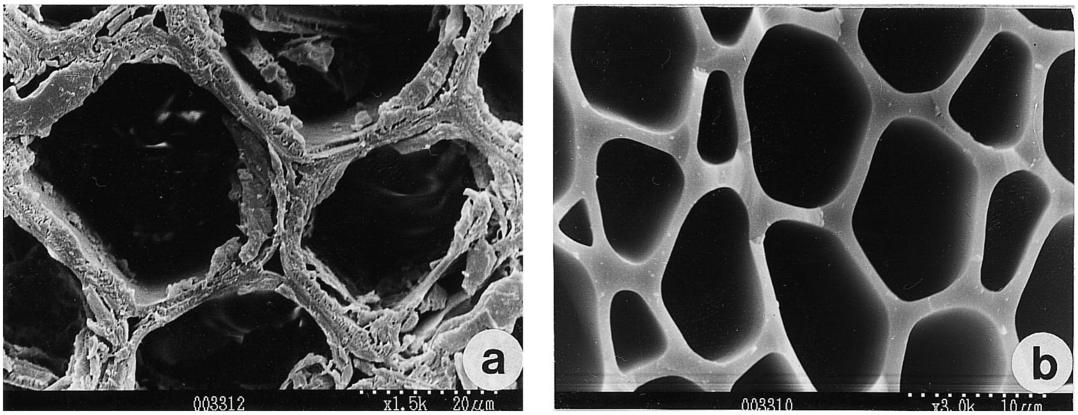


Fig. 8. Scanning electron micrographs of Recent experimentally charred pine (*Pinus*) wood charcoal. (a) Sample charred at 200°C for 1 h showing multilayered cell walls. (b) Sample charred at 450°C for 1 h showing homogenised cell walls.

microscopy and by scanning electron microscopy. They showed that above 370°C cell walls may begin to crack, especially along the middle lamella, and over 600°C may fragment. Tiny fragments resulting from this breakdown are termed inertodetrinite by coal petrologists (Jones, 1993; Taylor et al. 1998).

Shrinking of wood and other structures such as flowers during charring has been noted (Prior and Alvin, 1983; Scott and Jones, 1991b; Lupia, 1995). This may give rise to fire cracks (Scott, 1989) or other types of distortion such as the enlargement of wood rays (Harris, 1958). Such cracks have also been seen in fossil woods (Jones, 1993). 'Checking' or pull-apart cracks have been interpreted as desiccation features preserved when the wood was charcoalified (Jones, 1993).

In some cases a fire may not only burn surface litter but also burn peat. Such burnt peat shows characteristic morphology when seen in reflected light. In particular, degassing pores may be identified (Petersen, 1998).

4.4.2. Chemistry

Chemical studies have been undertaken by several authors on experimentally charred wood. Changes in CHN and O are reported (Cope, 1980; Jones et al., 1997). Increased temperature gives rise to a dramatic loss of oxygen and increase in percentage carbon. The most dramatic changes appear to take place between 200 and 400°C.

Using ^{13}C NMR, Jones (1993), interpreting CPMAS TOSS spectra, recognised clear changes in the range 300–600°C. He found that in untreated wood there was a range of peaks due to polysaccharides, lignin, etc., but that by 600°C there was a single large peak attributable to broad unidentified aromatics and a smaller peak attributable to acid groups. This confirms the view that, with heating, polysaccharides start to break down before lignin.

Changes have also been tracked using FTIR spectra. Guo and Bustin (1998) noted distinct differences in the spectra of wood charred at 320 and 480°C. Spectra of woods charred at 320°C showed intense peaks at 1708, 1615, 1317–1315 and 1708 cm^{-1}. They interpreted peaks at 1708 cm^{-1} to represent an acid C=O group, which they considered typical of low temperature charcoal. The 1317–1315 cm^{-1} peak was taken to represent absorption by aliphalic substances and the peaks at 1615 and 1708 cm^{-1} to represent the aromatic C=C ring stretching vibrations. Heating up to 480°C produced a decline in intensity of C=O group deposition and the aromatic CH_x stretching vibration and a rapid increase in intensity and definition of aromatic CH out-of-plane deformation. Peaks due to C=C ring stretching vibration also occurred. Marked differences are shown, therefore, between the woods heated up to 320 and 480°C. Using FTIR spectra these authors found differences between charcoals formed at

similar temperatures but from different plants and between different tissue types from the same plant. Collectively, they concluded that "wood tissue charcoal has more aromatic C=C structures, oxygen-containing groups including C=O, C—O—C and —OH and aromatic substituted groups than cortex tissue charcoal".

The data show that experimentally produced charcoals bear striking chemical similarities to fossil charcoals (fusain) (Cope, 1980; Guo and Bustin, 1998).

4.5. Settling and flume experiments

Although there have been several studies that considered the wind transport of microscopic charcoal particles (Clark, 1988), there has been little research on the transport, settling and depositional behaviour of larger charcoal particles by water. Recently, a series of experiments has been undertaken by Nichols and his colleagues on the settling behaviour of charcoal (Nichols et al., 2000). Using a simple wave tank (Nichols, 1999), Vaughan and Nichols (1995) found that the time taken for charcoal to settle was directly related to charring temperature (Fig. 9). They also showed that physical changes in the charcoal seen during increasing temperature (Scott and Jones, 1991b) were directly responsible for this behaviour. Key features included the homogenisation of the cell walls followed by cracking and final disintegration of the walls.

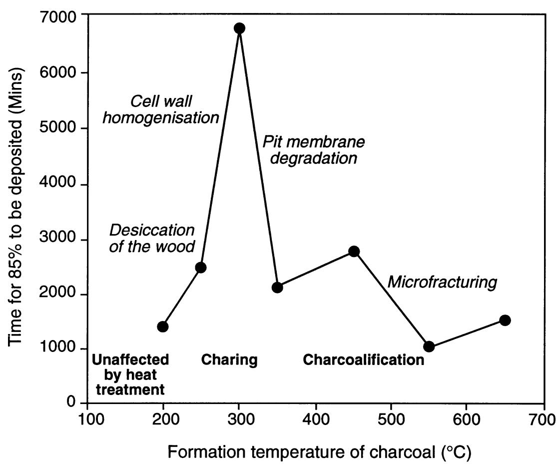


Fig. 9. The settling of experimentally charred wood in a wave tank showing effect of charring temperatures and significant changes in the morphology of the wood (*Pinus*). [After Vaughan and Nichols (1995)].

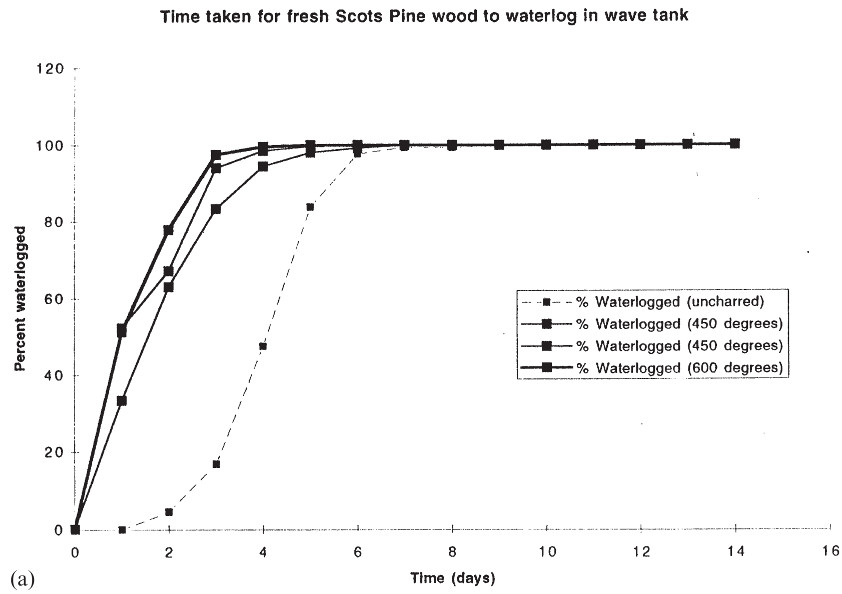
A series of subsequent experiments by Nichols et al. (2000) showed differences in settling time between fresh and charred wood (Fig. 10a), between charcoals of different genera of wood (Fig. 10b), and between charcoalified organs of the same taxa (Fig. 10c). Charcoals of the same taxon and organ charred at different temperatures (Fig. 10d) also showed different settling times. Such differences in settling time are likely to mean that an assemblage of charred and uncharred organs from a fire may become separated during water transport even before joining the bed load (Scott et al., 2000a).

To be preserved in the fossil record the charcoal must become incorporated into sediment. In slow or stationary water it will eventually settle more or less passively among fine-grained sediment. In faster flowing water the charcoal may travel within the bedload (Nichols, 1999). Experiments have shown that there is an optimum flow rate of 35 cm s^{-1} for small charcoal fragments to become entrained in ripples formed by bed load movement (Nichols et al., 2000).

5. Implications of the occurrence of fossil charcoal: atmosphere and climate

5.1. Atmospheric oxygen

Fire cannot be sustained without free oxygen in the atmosphere (Pyne et al., 1996, Fig. 2). Combustion of plant material (fuel) uses oxygen and releases carbon dioxide and heat (Fig. 2). In the reactions that take place there is a pre-ignition phase in which there are endothermic reactions (see Section 2.3). This is often supplied by a point source of heat such as a lightning strike. Once the fuel has been ignited the heat which has been generated may sustain the burning process. Volatile products will be released and will be also burned. If there is a limit on oxygen supply then the fire will go out (Pyne et al., 1996). The moisture content of the plant material may also play a



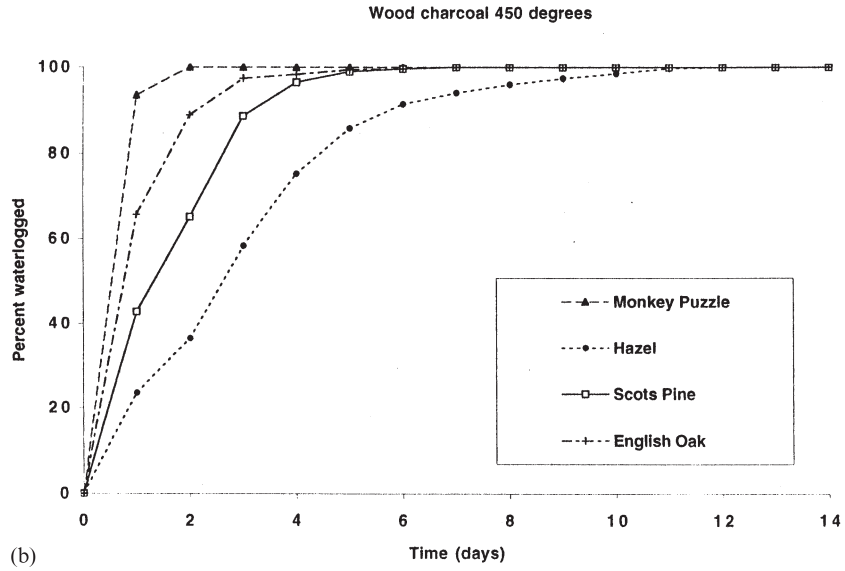
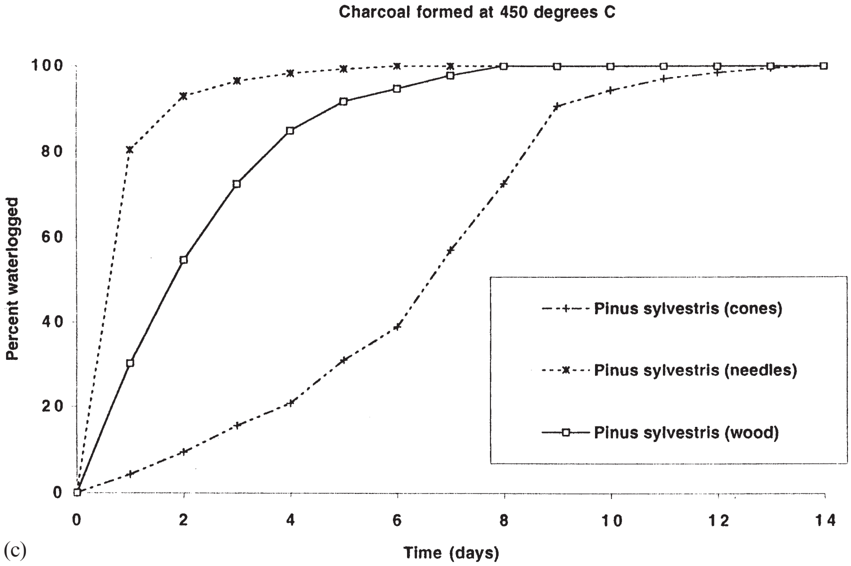


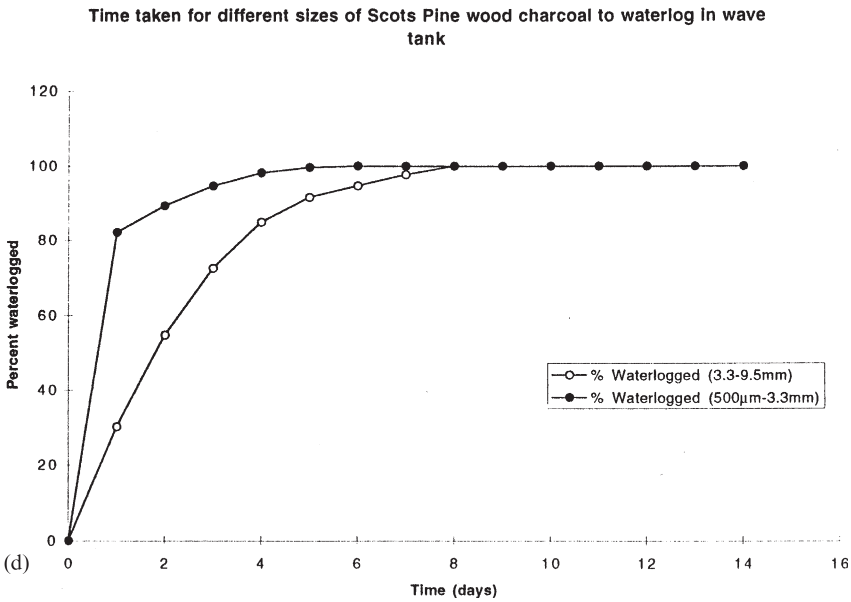
Fig. 10. Settling experiments on experimentally charred plant material (from Royal Holloway Campus). (a) Scots pine wood; uncharred, charred at 450°C (two runs) and 600°C. (b) Wood of monkey puzzle, hazel, Scots pine and English oak charred at 450°C. (c) Organs of Scots pine (*Pinus sylvestris*) charred at 450°C: wood, needles and cones. (d) Two size fractions of Scots pine wood charred at 450°C.

crucial role in allowing a fire to be sustained (Watson et al., 1978).

Cope and Chaloner (1980) and Chaloner (1989) have pointed out that fire may only be sustained with oxygen levels in the atmosphere of 7%, that is 0.3 of the present atmospheric oxygen (PAL). These authors considered the minimum level for methane and carbon monoxide to burn with a given level of pre-mixed oxygen, citing the work of Coward and Jones (1952). In a discussion of



(c)



(d)

Fig. 10. (*continued*).

the minimum oxygen requirement, both Clark and Russell (1981) and Cope and Chaloner (1981) concluded, based upon sustained combustion of wood already ignited, that 13% or 0.6PAL was a more realistic estimate (Fig. 11).

In the fire fundamentals triangle of Pyne et al. (1996) (Fig. 2), oxygen, heat and fuel must be present for fire to exist. Whilst vascular land plants have existed on land since the Silurian, it was not until the Devonian that sufficient fuel may have accumulated for fires to become widespread. Spread of vascular land plants may be linked to increasing oxygen in the atmosphere. The first trees did not evolve until the mid-Devonian, but it was not until the late Devonian that there were extensive coastal forests (Scott, 1980; Collinson

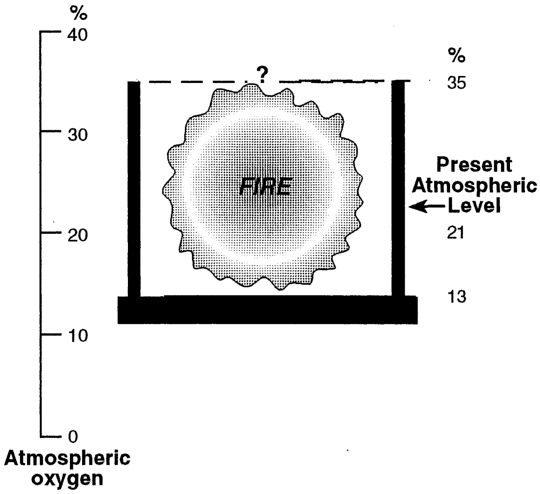


Fig. 11. The fire window [after Jones and Chaloner (1991)] illustrating the range of atmospheric oxygen which may sustain fire.

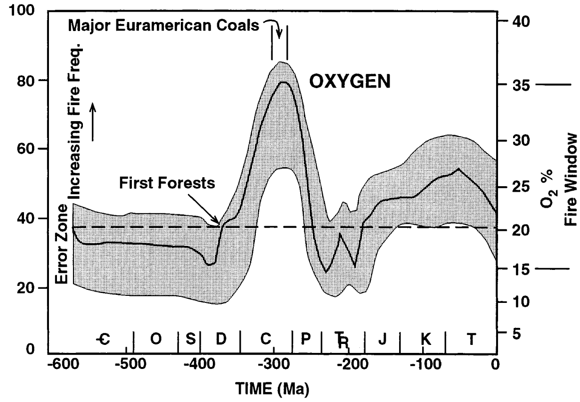


Fig. 12. Proposed atmospheric oxygen levels over the last 600 million years [adapted from Berner and Canfield (1989)].

and Scott, 1987). This period coincides with some of the oldest records of charcoal in the fossil record.

According to charcoal occurrence, therefore, oxygen levels in the atmosphere must have remained at least at 13% or over since the late Devonian. Experiments have shown (Watson, 1978) that increasing oxygen levels in the atmosphere above 21% (PAL) would increase the probability of fire. Further, Watson et al. (1978) consider that the probability of fire would be increased by 60% with an increase of only 1% of oxygen. These authors also consider that an increase to 25% oxygen would lead to the possibility of very wet plant material burning. A level of 25–35% oxygen, Watson et al. (1978) suggest, would be incompatible with the existence of land-based vegetation, as it would be consumed by raging fires.

In modelling atmospheric oxygen through time, Berner and Canfield (1989) propose a rapid rise in atmospheric oxygen from the late Devonian to the late Carboniferous (Fig. 12). These authors suggest that oxygen levels were very high during the Carboniferous and Permian, below PAL during the Triassic and above PAL for the rest of the Mesozoic and Tertiary (Fig. 12). Their 'best estimates' show, for example, oxygen levels at about 35% for the Carboniferous. Even with a wide error estimate they indicate a minimum level of about 26% for the Carboniferous. Consideration of the data of Watson et al. (1978) would suggest that such raised oxygen levels would lead to more common, more extensive and more intense fires. Berner and Canfield (1989) acknowledge that higher O_2 levels would lead to more forest fires. Robinson (1991) has attempted to correlate fusinite and semifusinite abundance with reconstructed O_2 values but found the data inconclusive. There may be problems in the data set used, as it came solely from coal seams.

Raised oxygen levels in the Carboniferous have been recently supported by studies of insects. During the Carboniferous many insects grew to a large size, which, several authors have considered, could only happen with increased oxygen levels (Dudley, 1998). Evidence for widespread fires is first seen in the Carboniferous (Scott and Jones, 1994; Falcon-Lang, 2000). Little is known about fire intensity or fire frequency, and until more data are available the atmospheric oxygen model problem cannot be settled. The differences between the views of Watson et al. (1978) and Berner and Canfield (1989) demand more experimental work.

5.2. Fire and climate regimes

Fosberg et al. (1993) pointed out that: "Fire behaviour and fire effects are the result of both

ecosystem structure and composition (fuels) as well as climate" (Fig. 2). Climatic zones are strongly linked to fire and as such can be modelled even for past time periods (Beerling et al., 1998). In any consideration of fire susceptibility both precipitation and temperature are important (Terasmae and Weaks, 1979; Fosberg and Levis, 1997). Equally so is the build up of potential fuel. Even today small changes in climate may trigger an increase in fire occurrence. In those cases fire return intervals may shorten or more intense fires result, or in some cases areas that are generally not fire prone may burn, having a dramatic effect on the ecosystem (Johnson, 1984; Swetnam and Betancourt, 1990; Meyer et al., 1992).

The geological record introduces a time dimension of a greater scale. Even in the more recent past fire histories have been shown to change, and thus have been linked to climate change in terms of hundreds or thousands of years (Clark, 1988; Wang et al., 1999). As yet there has been no attempt to look at fire frequency or intensity with relation to climate change on a longer time scale (millions of years).

5.3. Fire in temperate and boreal regions

Fires are common in many of the world's temperate and boreal regions (Johnson, 1992; Wein, 1993; Trabaud et al., 1993; Racine et al., 1995; Pyne et al., 1996). The build up of a fuel load, together with a seasonal climate, ensures that fires may be regular and in some cases severe and widespread (Wein, 1993). Fuel load may be high because the cooler temperatures suppress fuel decomposition (Wein, 1993).

Within Mediterranean areas most fires are started by human activity, but still 2% of the area burned annually is from lightning fires (Trabaud et al., 1993). Some types of vegetation are maintained by fire, such as heathlands developed on poor soils (Trabaud et al., 1993). There has been much research on the relationship between fuel consumption, fire return interval and climate in North American ecosystems (Martin, 1982; Christensen, 1987). In general, fire return intervals increase when the climate becomes warmer and drier or colder or wetter (Martin, 1982).

5.4. Fire in tropical regions

Whilst fire has had a long history in the tropics, not all vegetation types are fire prone (Batchelder, 1967; Sanford et al., 1985). In general, the high humidity in many forests means that combustibility will be low (Batchelder, 1967). This implies that fuel levels will build up, so that when a fire occurs it may be catastrophic (Johnson, 1984; Pyne et al., 1996).

Most fires in the tropical regions occur in the drier areas, such as grasslands and open dry forests where fires would spread more easily. Many savanna areas burn on a regular interval with short fire return intervals, and the small resulting wind-blown particulates may be widespread (Bird, 1997). Because many grasses have a different isotopic composition from other plants, such savanna or grassland, burning is easily identified in sedimentary charcoal (Bird, 1997; Wooller et al., 2000).

5.5. Fires in mire systems

Surprisingly, many peat-forming systems are seen as fire-prone (Komarek, 1973). They represent areas where there is a large reserve of potential fuel (Cameron et al., 1989). During dry periods fires may burn that may have a dramatic effect upon the ecosystem and environment (Cypert, 1973; Cohen, 1974; Rollins et al., 1985).

6. The first fires

Plants first invaded the land during the late Silurian, but at first must have been rather restricted in distribution. Extensive colonisation of a wider range of habitats took place through the Devonian. Probably, therefore, enough fuel was available by the mid-late Devonian for the development of extensive wildfires. A key event is likely to have been the evolution of trees. Some tree-like forms existed in the mid-Devonian, but it was not until the late Devonian that there were extensive forests of trees with planated foliage forming crowns (Meyer-Berthand et al., 1999).

Atmospheric oxygen levels are also a key factor (Cope and Chaloner, 1980). During the early

Palaeozoic oxygen levels remained low. By the Devonian they had risen to a point where fire might have been sustained (Berner and Canfield, 1989) (Fig. 12). Evidence for Devonian fire might, therefore, be expected.

6.1. Earliest Devonian records

Recognition of charred plants from the early Devonian has proved difficult. There are no records of extensive charcoal deposits before the late Devonian. Burgess and Edwards (1988) reported a plant (*Nematasketum*) with homogenised cell walls that was interpreted by Robinson et al. (1997) as evidence of fire. Until more material becomes available this record must be treated with caution.

6.2. Late Devonian Callixylon

Fragments of charred secondary wood of *Callixylon*, an early tree from the late Devonian, show features of true charcoal. The material was first described by Beck et al. (1982), who doubted a fire origin. Subsequent work by the author and Jones (1991) suggests that it is charcoal, a view promoted by Chaloner and coworkers (Cope and Chaloner, 1985; Jones and Chaloner, 1991). Only isolated fragments were found.

More extensive charcoal deposits have been recently discovered in late Devonian clastic sediments of the Catskill Delta in Pennsylvania. Research on this material is early, but it presents the earliest evidence known of widespread wildfire in the fossil record (Pfefferkorn and Cressler, written communication, 1999).

6.3. Devonian coals

Coals are rare in the Devonian. Petrographic studies on most Devonian coals indicate that they are dominated by cuticles (Han, 1989), but apparently no inertinite has been found. Inertinites were reported by Goodarzi et al. (1989) in Middle–late Devonian coals of Canada, but no illustrations were provided. This suggests fire in a mire system. Other records appear less secure, such as that of fusinite in Silurian sediments. A review with new data is that of Rowe and Jones (2000).

7. Carboniferous conflagrations

Fossil charcoal has long been known in the Upper Carboniferous coal seams of South Wales (Lyell, 1847; Scott, 1998). Fire and charcoal in Carboniferous coals became a major subject of debate in the late 19th and early 20th centuries (Muck, 1881; Stützer, 1929). Most of the debate on fusain until the 1970s was focused on its recognition as fossil charcoal formed by wildfire rather than on the identity of the plants preserved or on fire ecology (Scott, 1989, 1998). Extensive Lower Carboniferous charcoal deposits, first described from Co. Donegal, Ireland (Scott and Collinson, 1978), were interpreted as products of a major wildfire. The published record of Carboniferous fires is now extensive (Scott and Jones, 1994; Falcon-Lang, 2000) and only a summary is presented here.

7.1. Early Carboniferous widespread fires

7.1.1. Tournaisian of southern Scotland

Non-marine clastic and volcanogenic sediments in the Cementstone Group of Southern Scotland contain isolated charcoal fragments (Scott 1988, 1989). These include wood and stem fragments, pollen organs and sporangia (Scott 1989, 2000) (Fig. 13). Most charcoal fragments are isolated and no substantial deposit has been located. Small charcoalified fragments of plants have been recovered from late Tournaisian volcanogenic sediments from the Kilpatrick Hills. Plants also occur as calcareous permineralisations (Scott et al., 1985) and are dominated by various genera of ferns (Scott and Galtier 1985).

Some of the fires may have been started by volcanic activity (Scott, 1988, 1990b). Charcoalified lycopsids, reported from volcanic ashes in Oxroad Bay, probably represent monotypic vegetation that was burnt and washed into a lake (Bateman and Scott, 1990).

7.1.2. Tournaisian of eastern Canada

Isolated charcoal fragments have been discovered in the fluvio-lacustrine sequence of the Tournaisian Horton Group, Nova Scotia (Falcon-Lang, 2000; Falcon-Lang and Scott, 2000). At one

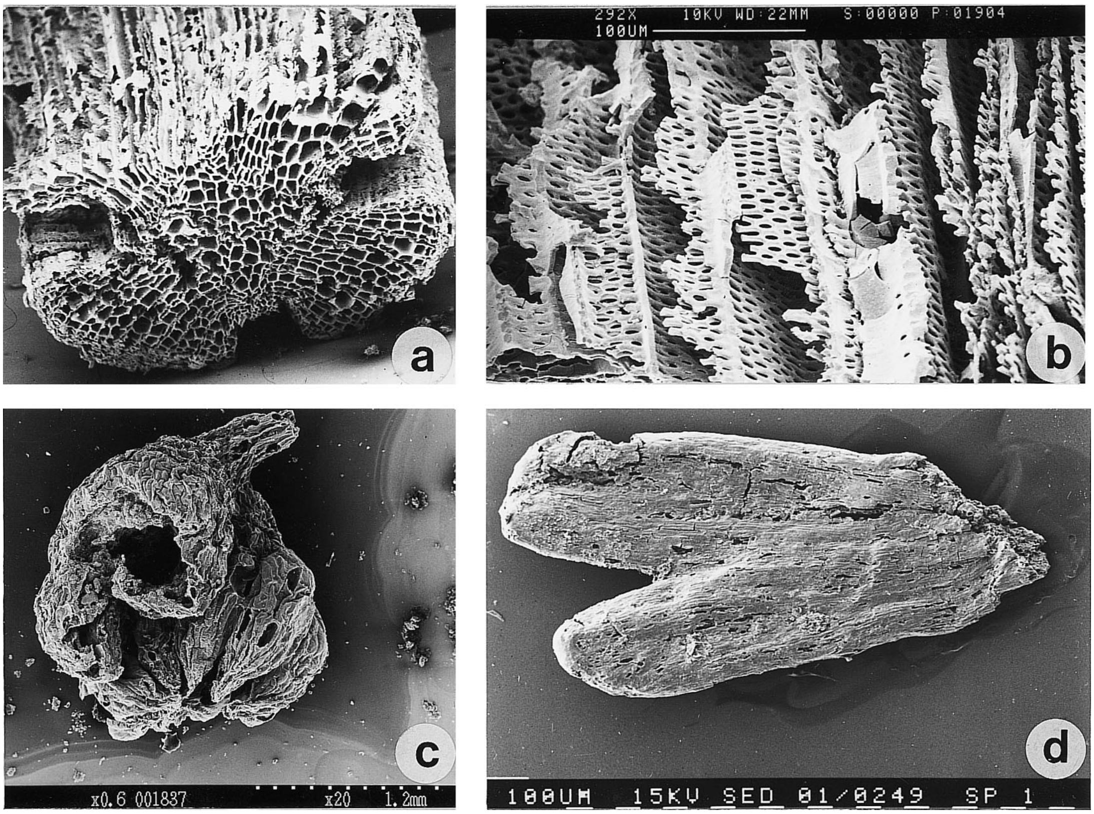


Fig. 13. Scanning electron micrograph of charcoal from the Lower Carboniferous of Scotland. (a), (b) Pteridosperm axis, Cementstone Group, Tournaisian, Lower Carboniferous, Scotland. NGR NT821560. (a) ×40, (b) ×200. (c) Pteridosperm pollen organ. Cementstone Group, Tournaisian, Lower Carboniferous, Scotland. NGR NT821560. (d) Pteridosperm leaf, Oil Shale Group, Viséan, Lower Carboniferous, Scotland. NGR NS265864.

localility, Martock, varve-like sediments contain numerous charcoal-rich horizons recording a regular fire cycle. Marginal lacustrine sequences at Three Mile Plain show bedding surfaces with abundant charcoal. Some of this is of gymnosperm origin and some lycoposid, but as yet no systematic study has been undertaken.

7.1.3. Viséan of western Ireland

Extensive charcoal deposits occur at several localities in Donegal and Mayo in marginal marine clastics and carbonates of early Viséan age. Charcoals from the Shalwy Beds (Fig. 14) of Donegal were shown to include lycopsids and gymnosperms (Scott and Collinson, 1978). One horizon containing fusain was found to be extensive and was interpreted by Nichols and Jones (1992) as the result of a major wildfire comparable with the Indonesian fire of 1982–83 (Johnson, 1984) (Fig. 15). Similar deposits have also been found by the author in inland sites in Mayo.

Falcon-Lang (1998) investigated the impact of a major wildfire on an early Viséan environment in North Mayo, Ireland. The 28 m sequence of carbonates and clastics was shown to include a horizon with abundant fossil charcoal containing abundant '*Dadoxylon*'-type (gymnospermous) wood fragments. Falcon-Lang (1998, 1999b) showed that the larger fragments recorded growth rings which he interpreted as rings formed in response to tropical rainfall seasonally linked to seasonal circulation. He concluded that the sequence recorded a major wildfire in the catchment area where the burning induced significant erosion (Fig. 16). The charcoal

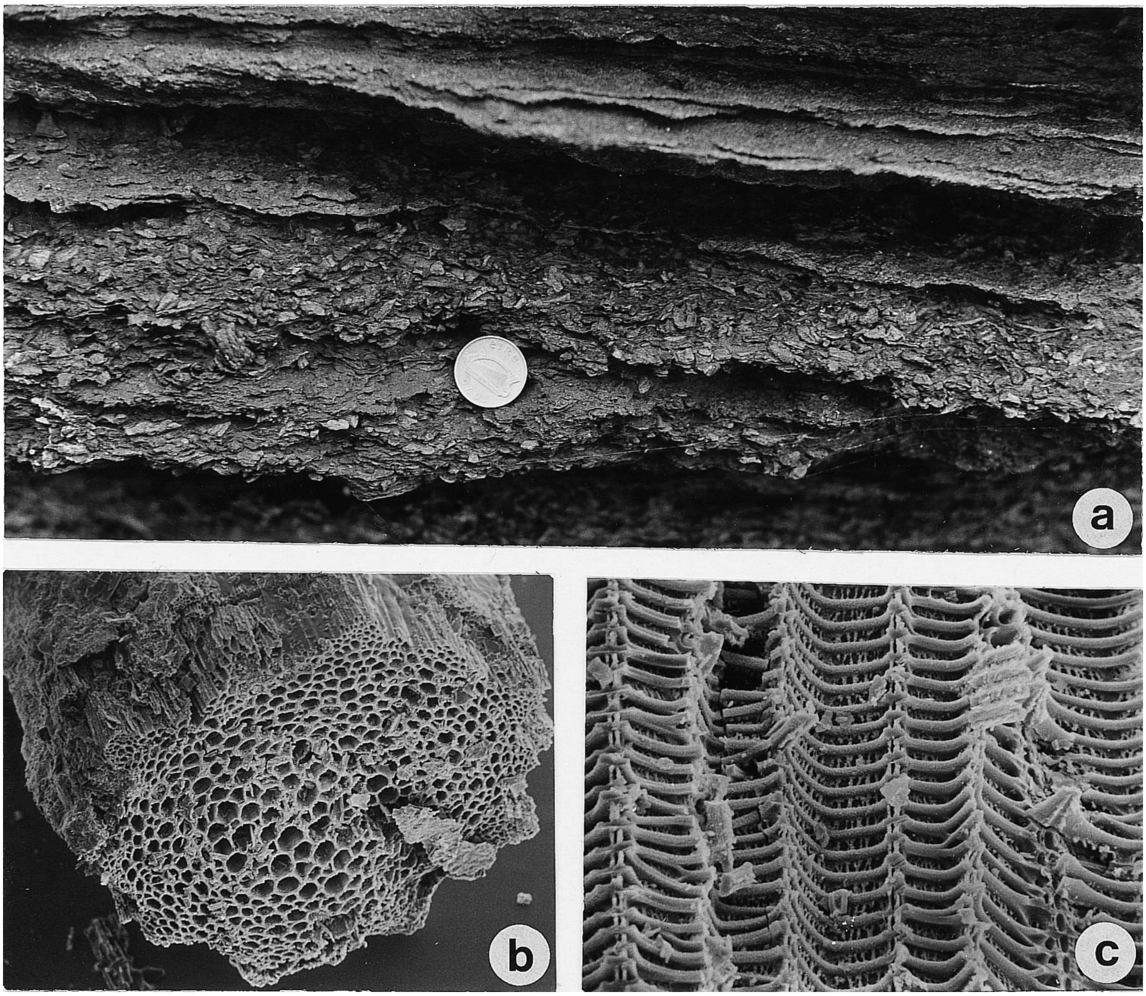


Fig. 14. The Lower Carboniferous charcoal deposit from Shalwy, Donegal, Ireland. (a) Field view of charcoal-rich layers. (b), (c) Scanning electron micrographs of charred lycopsid steles (*Oxroadia*) from the charcoal layers: (b) ×60, (c) ×300.

and eroded soil were removed and dumped in a marine estuary, causing an extensive fish kill. This is the first report of an ecological disaster caused by a Pre-Quaternary fire.

7.1.4. Viséan of Scotland

Extensive charcoal deposits associated with volcanogenic sediments and lavas have been reported from several horizons in Scottish Viséan deposits (Scott, 1988, 1990b; Brown et al., 1994; Scott et al., 1994; Falcon-Lang, 1999a). While some of the charcoal fragments may represent plants burnt by direct contact with hot lava (Rex and Scott, 1987) others may have resulted from wildfires started by volcanic activity (Scott and Rex, 1987; Brown et al., 1994). At East Kirkton, Scotland, numerous ash layers contain abundant gymnospermous wood charcoal that was probably washed into a lake following wildfires on the flanks of a nearby volcano (Brown et al., 1994; Scott and Jones, 1994).

Another lake sequence at Kingswood has been shown to contain abundant charcoalified remains of a variety of plant organs (Scott et al., 1985; Scott, 1990b). Those found in the lacustrine carbonates probably come from two distinct plant communities: a non-charred herbaceous lycoposid

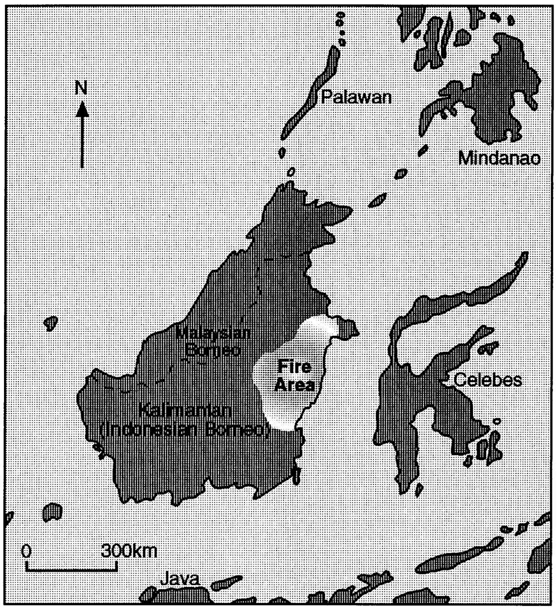


Fig. 15. The area affected by the great fire of Borneo 1981–82 [after Pyne et al. (1996)].

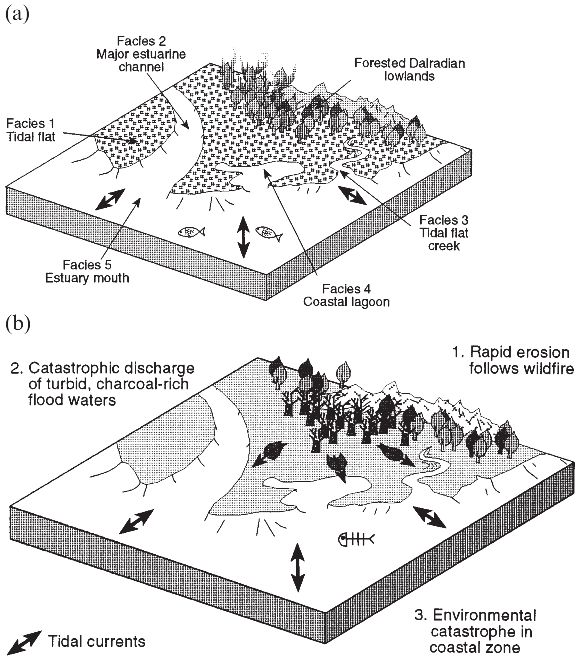


Fig. 16. The area around Mayo, Ireland, in the Lower Carboniferous before and after a major fire [after Falcon-Lang (1998)]. (a) Before the fire. (b) After the wildfire, showing its effects.

community and a charred community dominated by pteridosperms and gymnosperms. Wood, leaf and fertile organ charcoalified fragments are recognisable (Scott, 1990a,b). Growth rings in woods indicate periods of drought when fires may have occurred (Falcon-Lang, 1999b).

7.2. Fires in the Upper Carboniferous Coal Measures: evidence from coals

Fusain is a common constituent of most Carboniferous coals (Taylor et al., 1998) (Fig. 5), often accounting for more than 10% and rarely over 20% of the seam (Shearer et al., 1995). It may occur in bands or dispersed through the coal (Scott and Jones, 1994). Petrographically, it comprises fusinite, semifusinite and inertodetrinite (Taylor et al., 1998). Carboniferous coal seams may be several metres thick, with a compaction ratio averaging 10:1 as a consequence of the transformation of peat to bituminous coal. This means that they often represent peats that were 10–25 m thick (Calder and Gibling, 1994). If a rate of peat accumulation of 2 mm per year is used [comparable to the accumulation rate of tropical peats today (McCabe, 1984)], then the coal seams may have taken more than 10,000 years to form. Fire return cycles of 100 years would, therefore, lead to many charcoal horizons occurring within each coal seam. Sampling and recording fusain-percentage data based upon whole coals, or even for units within the coal, does not lead to useful estimates of the nature, intensity or fire return intervals. Information on continuous or closely sampled coals is rarely published.

Fusain is common in the Namurian coals of Scotland and Poland (Scott, personal observation). Most of the data on its Upper Carboniferous occurrence come from the Westphalian coals of Europe and North America.

Bartram (1987a,b), in her study of the Barnsley Seam, adopted a close sampling procedure. Analysis of the inertinite fraction showed a background value with several distinct peaks, which presumably resulted from more severe or local fires (Fig. 17). The nature of these fires has not yet been investigated, in terms of vegetation, intensity nor extent. Vegetational data can also be obtained from the coal balls that occur in some coals (Scott and Rex,

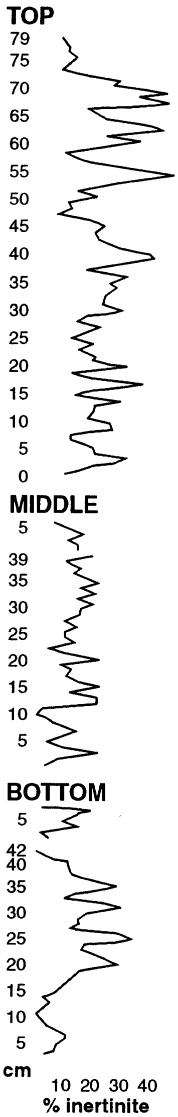


Fig. 17. Distribution of inertinite macerals (fossil charcoal) through the Lower Barnsley Seam, Yorkshire [data from Bartram (1987a)].

1985): Phillips and coworkers (Phillips, 1981; Phillips and DiMichele, 1981; DiMichele and Phillips, 1994) showed that charcoalified pteridosperms preserved in them may represent a fire-prone vegetation (Scott and Jones, 1994)

The occurrence of wildfire in Carboniferous mire systems of tropical Euramerica has been debated for over a century (Scott, 1989). White [in Stützer (1929)], for example, wrote that "it is quite impossible for me to conceive of fusain as exclusively the result of forest fires". An incredulous Muzumbar [in discussion of Austen et al. (1966)] wrote "it is difficult for us to accept the view that temperatures of the order of 600°C or so must have been involved in forming fusinite. One would have to imagine the raging forest fires during primordial times in all areas of coal formation and right in the peat bogs". Nevertheless, it is now generally accepted that fusain is charcoal formed as a result of wildfire (see Sections 3–5), and climate modellers recognise fire as an important element in Carboniferous ecosystems (Beerling et al., 1998). However, our understanding of fires in the mires is still rather simplistic.

7.3. Fires in the Upper Carboniferous Coal Measures: evidence from clastic sediments

Whereas fusain has been widely reported from coals, less is known about the occurrence of fossil charcoal in the associated clastic facies. Charred pteridosperm and fern leaves were reported by White (1908, 1933) and Remy (1954) but their generation by fire was questioned (Schopf, 1975).

Scott (1978) recovered a range of charcoalified plants from floodplain shales in the Coal Measures of Yorkshire. These included pteridosperms, lycopsids, cordaites and conifers (Scott, 1974; 1984; Scott and Collinson, 1978) (Fig. 18). The assemblage was interpreted as resulting from a fire outside a mire (Scott and Chaloner, 1983).

Most charcoal discovered in the field was formed from wood or periderm tissues of lycopsids or cordaites. In the Westphalian A/B coal measures at Joggins, Nova Scotia (Scott and Calder, 1994; Scott, 1998) (Fig. 19), it occurs within the bases of lycopsid trees at several horizons. Falcon-Lang (1999c) demonstrated that the charcoal in the base of one *Sigillaria* was formed by the burning of the tree itself. He considered that this individual was part of a fire-prone community dominated by *Sigillaria* and medullosan pteridosperms. He further identified abundant wood charcoal in river channel deposits dominated by *Cordaites* (Falcon-Lang and Scott, 2000). This community apparently occupied a dry, extra basinal upland niche where

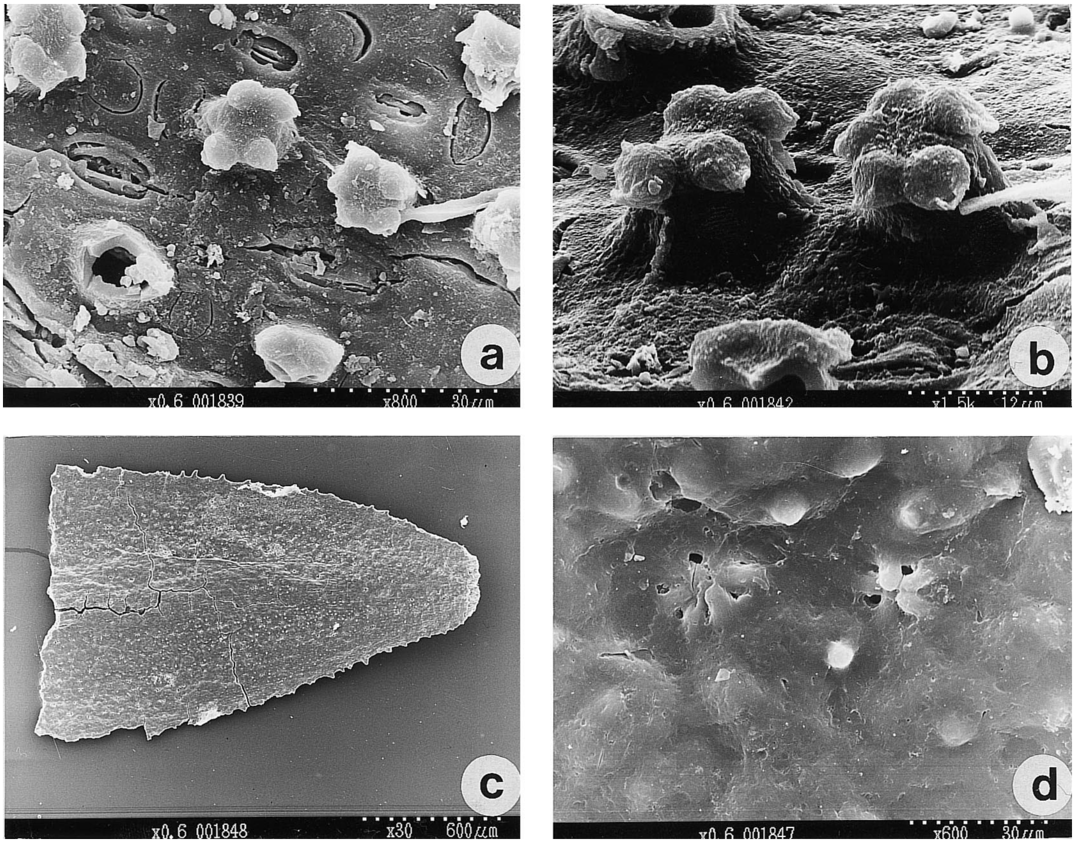


Fig. 18. Scanning electron micrograph of charred leaves from Upper Carboniferous sediments. (a), (b) Cordaite leaf showing stomata and glandular hairs from the Westphalian B Coal Measures of Swillington, Yorkshire. NGR SE385315. (c), (d) Conifer leaves of *Walchia* from the late Carboniferous of Garnet, Kansas, USA, showing toothed margin and sunken stomata.

wildfires de-stabilised an upland slope and enhanced erosion and deposition.

7.4. Fires in the Upper Carboniferous: evidence from marine sediments

Charcoal has been rarely reported from marine Upper Carboniferous rocks, but is certainly not uncommon. Scott et al. (1997) noted scarce charred plant fragments in goniatite-rich carbonates deposited during a marine high stand in the English Namurian. The charcoal was associated with anatomically preserved plants (calcareous permineralisations) dominated by *Cordaites* and thought to represent an 'upland' community. Isolated fragments of wood charcoal also occur in marine sediments in the central basin in North America of late Carboniferous age (Fig. 20), but no systematic study has been published.

7.5. Carboniferous fires and atmospheric oxygen

As has already been noted, the Carboniferous was a period of high oxygen concentration in the atmosphere. This suggests that fires have been more frequent during this period. Certainly sufficient fuel was available, but moisture contents were probably high in such tropical mire systems. Fires are rarer in tropical rain forests today (Pyne et al., 1996), but the increased oxygen content of the atmosphere during Carboniferous times may have allowed the spread of fires in to damper

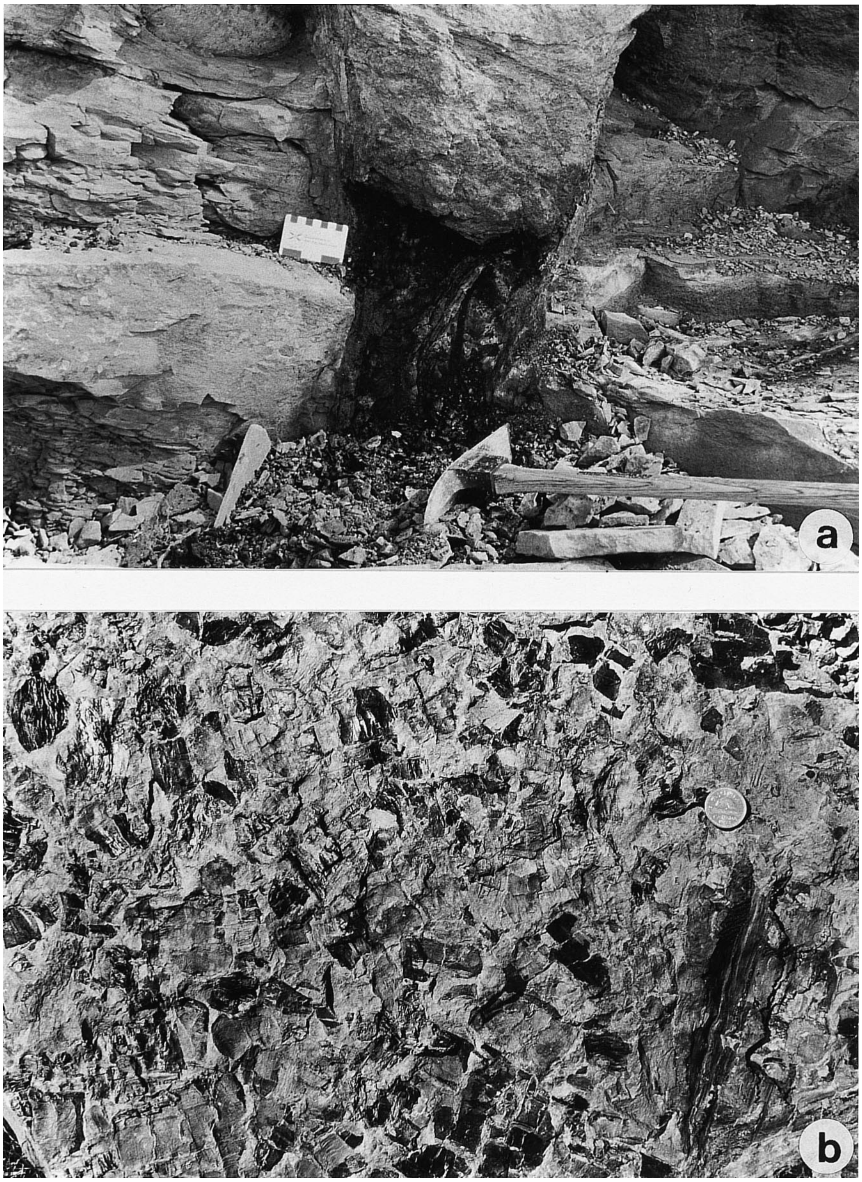


Fig. 19. Charcoal at the bases of upright lycopsid sandstone filled trunks, Joggins, Nova Scotia [from Scott (1998)]. (a) Upright trunk with a charcoal-rich base. (b) Abundant charcoal fragments at base of lycopsid trunk.

environments (Berner and Canfield, 1989). Fires may have been more common during slightly drier intervals. Microscopic charcoal has been found in palynological preparations from Coal Measure lacustrine sediments (Highton et al., 1991), but no systematic study has been undertaken, like those of coal sequences, to estimate fire intensities and frequencies. Falcon-Lang (2000), proposes lowland fire return intervals of 1–5 to 15–85 years as likely.

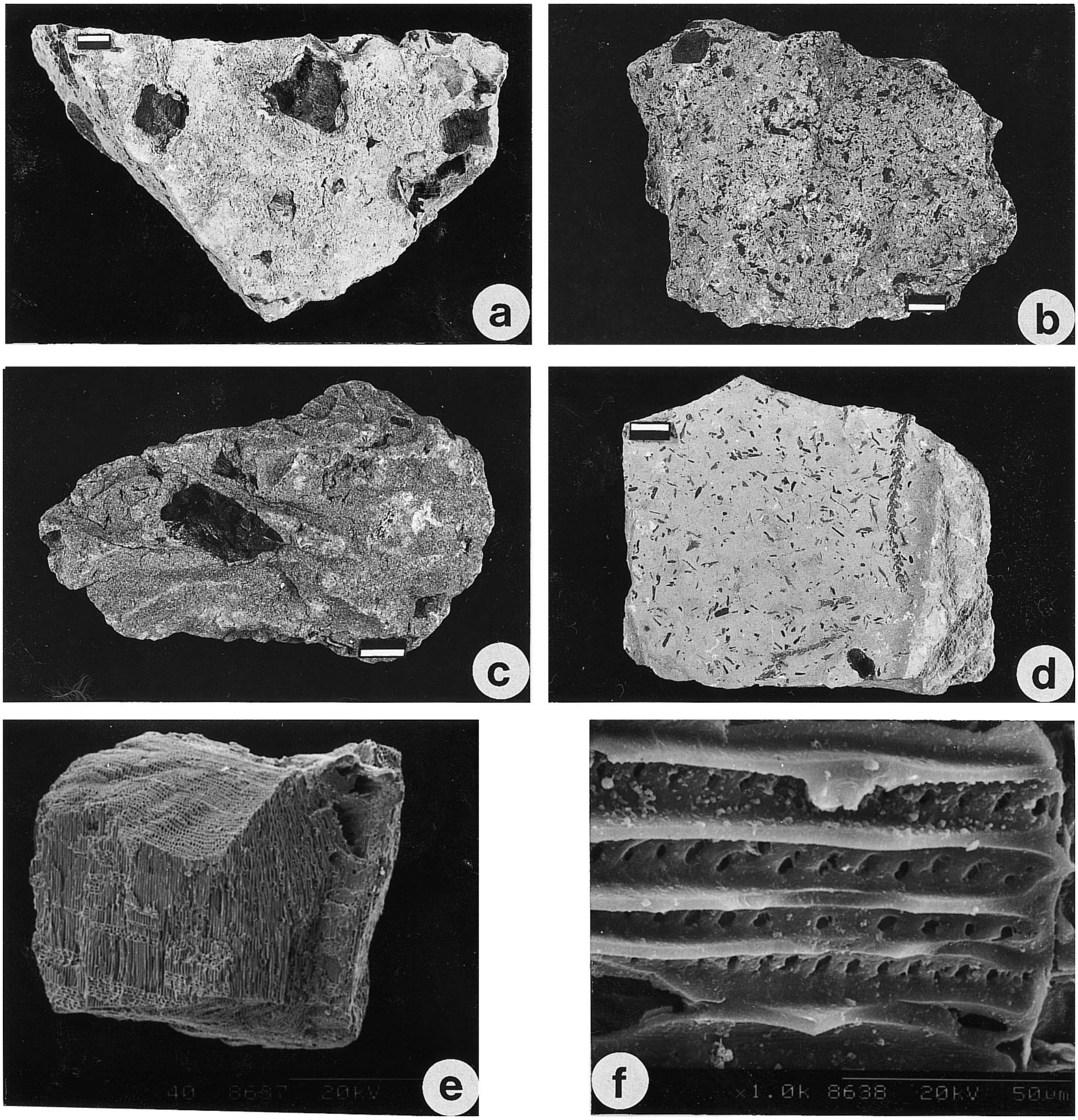


Fig. 20. Fossil charcoal from late Carboniferous and early Permian marine sediments from the USA. (a) Large charcoal fragments from channel sandstones, Pomona, Kansas, USA (scale 1 cm). (b) Small charcoal fragments from estuarine carbonates, Hamilton, Kansas, USA (scale 1 cm). (c) Charcoal fragment from marine limestone, Lower Permian, Oklahoma, USA (scale 1 cm). (d) Fine conifer leaf charcoal in estuarine limestones, Hamilton, Kansas, USA, late Carboniferous (scale 1 cm). (e) Scanning electron micrograph of isolated charcoal fragment from early Permian marine sediment, Oklahoma, USA (×15). (f) Detail showing wall pitting (×200).

8. Permian controversy

The major fall in atmospheric oxygen levels at the end of the Permian and during the Triassic may have generated a change in fire regime. Scattered data only hint at early Permian fires, and the later Permian fires in Gondwanaland are controversial and there are relatively few from the Triassic.

8.1. Problem of Gondwana inertinites

Gondwana Permian coals characteristically have a high inertinite content (Hunt, 1989; Taylor et al., 1998). Much of this is fusinite, semifusinite and inertodetrinite. Values of over 50% in coals from India, South Africa and Australia (Navale and Saxena, 1989; Taylor et al., 1998) have led many authors to doubt a wildfire origin (Taylor et al., 1989). Some cite the fact that much of the material is semifusinite and does not show the characteristic anatomical structures of 'charcoal' (Beeston, 1987). The doubts have led to the unusual theory of a cold origin for the inertinite (Taylor et al., 1989).

Recent work supports a wildfire origin for most, if not all of this material (Glasspool and Scott, 1997). Most of the inertinite shows low $<2\%$ reflectance and is typical of charcoals from surface fires (Scott et al., 2000a). Some shows higher reflectance and anatomical detail (Glasspool, 2000). Much of the material could be interpreted as burnt litter and duff, indicating a dominance of low-temperature surface and litter fires. Some of the fires may have occurred outside the mire and been followed by increased soil erosion, explaining the high mineral matter content of some Gondwanan coals (Falcon, 1989).

8.2. Permian records from the Northern Hemisphere

There are few published records of fossil charcoal from the Permian of Northern Hemisphere sites. Charcoal has been reported with bone accumulations in Permian sites in Texas (Sander 1987; Sander and Gee, 1990). This is exclusively wood charcoal. Larger charcoal accumulations occur in the Kilkenny deposits of New Mexico (W.A. DiMichele and D. Chaney, personal communication). Occasional rare fragments are found in the Permian marine sediments, including limestones, of Kansas, Oklahoma and Texas (Mapes et al., 1997). None of these deposits has yet been studied in detail.

9. Triassic tranquillity?

Although fusain had long been recognised in Carboniferous coal seams and considered by some workers to represent fossil charcoal and hence formed as a result of wildfire (Scott, 1989), Harris (1958) was the first to consider the occurrence and implications of fire in the Mesozoic; he described material from deposits in East Greenland (Rhaetic and Lower Liassic age), from North Yorkshire (Middle Jurassic) and South Wales (Rhaetic or Lower Liassic age fissure fills). Subsequent studies have been made on these and on other Jurassic and Cretaceous fusain deposits (see below).

9.1. Triassic charcoals of the USA and S. Africa

Very few records concern Triassic charcoal. Triassic coals in China do contain inertinite (China National Administration of Coal Geology, 1996), but little is known about its occurrence. Charcoal in clastic sediments is relatively rare. Thus, whereas the Molteno Formation of South Africa yields a very diverse flora from a range of sedimentary environments (Anderson et al., 1998), no charcoal has been reported, and none was found during recent fieldwork by the author.

Rare fragments of charcoal occur in the Triassic of the USA (S. Ash, personal communication) and some from the Petrified Forest are currently being investigated by the author.

10. Jurassic fire diversity

10.1. Rhaetic upland and lowland fires

Harris (1958) described small angular and rounded fusain fragments from the Rhaetic and Lower Liassic deltaic deposits of East Greenland. He further reported that the fusain was both abundant and widespread through a great thickness of rock in nearly every outcrop. This fusain was not identified.

Harris (1957) also reported fossil plants from the Rhaetic fissure fills in the Carboniferous Limestone of South Wales. He described the fossil charcoal and considered that nearly all of it belonged to the conifer *Cheirolepis muensteri* (Fig. 21) and comprised various organs with their internal tissues preserved. Charcoalified leafy shoots were recognised, as well as fragments

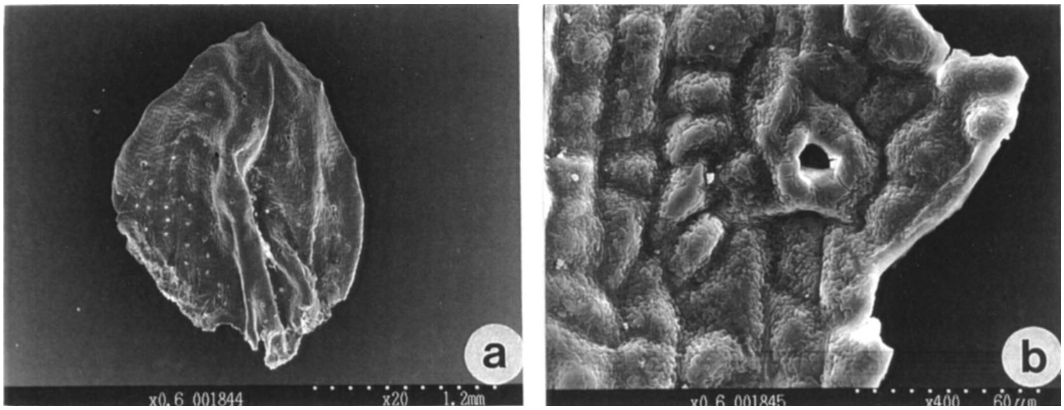


Fig. 21. Scanning electron micrographs of charred conifer leaves of *Cheirolepis muensteri* from the Rhaetic of South Wales NHM, T. Harris Collection, 35F.12. (a) Whole leaf. (b) Detail of leaf margin.

of secondary wood. Charcoalified wood of *Cheirolepis* formed nearly all the fossil material at one locality, Ewenny, and from one- to two-thirds at Cnap Twt. Charred bark, male cone fragments and microsporangia were also described. A few other charcoalified fragments included small pinna fragments of *Pterophyllum*. Later, Harris (1958) noted that both charred and uncharred material was present and that many pieces of wood showed fungal decay and well-preserved fungal chlamydospores in the rays. He observed that the same spores were found in the mesophyll of fusainised *Cheirolepis* shoots, and concluded that the wood represented twigs that had begun to rot before being burnt. Harris (1958) went on to suggest that the fire or fires passed quickly through *Cheirolepis* scrub and that the speed of the fire (a surface fire) indicated that no heavy timber was burnt. Interestingly, he also reported charred beetle remains, which recalls the recent heathland fire at Frensham, Surrey (Scott et al., 2000a).

The palaeogeography of these Welsh deposits is interesting in that the Carboniferous limestone hills then formed islands and the climate was wet enough to support vegetation (Harris, 1958). Fires would have swept through such 'upland' scrub and rain would have washed the debris into nearby fissures. The association of charred and uncharred material suggests minimal transport (Scott et al., 2000a).

10.2. Middle Jurassic fires in the North Sea region

10.2.1. Scalby

Harris (1958) also found abundant fusain in the of Middle Jurassic sandstones of Yorkshire. In addition to conifer wood charcoal, some horizons yielded small pieces of pinnules of the fern *Phlebopteris woodwardi*. Scott and Collinson (1978) noted the occurrence of well-preserved wood charcoal fragments in the Scalby Formation (Fig. 22). Cope (1980) described the preservation of some of the wood fragments and demonstrated other similarities to modern charcoal. Scott (1989) gave further information on the occurrence of

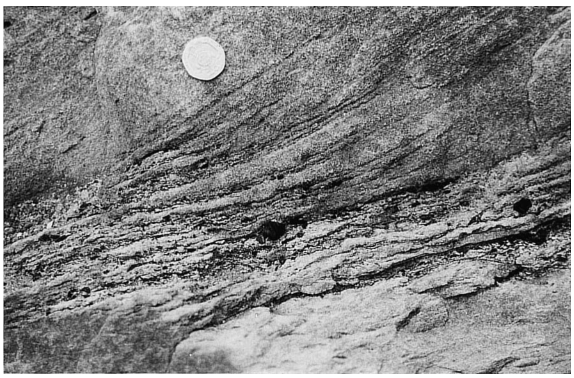


Fig. 22. Fossil charcoal in sandstones of the Middle Jurassic Moor Grit Member, Scalby Formation, Long Nab, Yorkshire, England (scale 2 cm) NGR TA030940.

charcoal in the Scalby Formation, presented data on the sizes of the fragments in the Moor Grit Member and illustrated some anatomy. All of the charcoal described has been of wood charcoal.

Cope (1993) described charcoals from the meander belt sandstone in the Long Nab Member of the Scalby Formation. Cope showed that the woods comprised predominantly pycnoxylic woods with rare cycadophytes, and identified these as *Taxodioxylon* S.L. (60%), ?*Ginkgo* (18%), ?*Araucarioxylon* (4%), *Cupresoinoxylon* (4%) and unnamable conifers (14%). Cope (1993) further noted that this suite contrasted markedly with the compression assemblages in the same formation (not necessarily associated with the charcoal). Cope (1993) concluded that the differences may have been caused by both ecological and sedimentological factors.

Nichols et al. (in prep.) have studied the occurrence of fusain in the sandstones of the Moor Grit Member. They noted entrainment in the rippled sandstones and used experimental data to show how wood charcoals can be incorporated into ripples at moderate velocities. Settling experiments have demonstrated that woods of different species, as well as different charred plant organs, settle at different rates (Nichols et al., 2000). Charcoal deposits in sandstones are therefore likely to show sorting. Clearly, wood charcoal dominates over charcoal of other organs (no non-woody charcoal has been recovered from the Moor Grit Formation sandstones), a feature suggesting at least some transport (Scott et al., 2000a).

Fires appear to be an important factor in the ecosystem dynamics of the Scalby Formation. Cope (1993) concluded that the conifer–ginkgophyte–cycadophyte flora was a fire-controlled climax community. It is possible that some of the fires took place on nearby uplands. There were certainly uplands north of the Yorkshire area (Leeder and Nami, 1979). Extensive fires, triggered by lightning, could have destroyed the upland conifer-dominated vegetation. Subsequent rainstorms then caused extensive erosion and sand- and charcoal-laden river systems. Some of the clastic sediments reached the northern North Sea in the Brent Formation deltas. Jones (1997) reported numerous charcoal horizons in the Brent Formation sandstones, indicating a regular fire regime.

Charcoal is not ubiquitous in the Yorkshire Middle Jurassic. The well-known Gristhorpe Plant Bed contains relatively little charcoal, indicating perhaps that lowland communities were less fire prone. It is also possible that the difference between the Cloughton Formation (containing the Gristhorpe Plant Bed) and the overlying Scalby Formation was due to climate, the fires becoming more frequent as it changed (becoming drier; Morgans et al., 1999).

10.2.2. North Sea

Coals yielding abundant charcoal occur in the Middle Jurassic Bryne Formation in the Central Graben of the North Sea (Petersen and Andsbjerg, 1996; Petersen et al., 1998). The series of coals are interpreted by these authors to have formed in a coastal plain environment in a seasonal warm temperate to tropical climate. Three mire types are described with Type 1 being the wettest and Type 3 the driest. The coals may contain up to 50–60% inertinite, which includes 10–20% fusinite (Figs. 23 and 24). This is interpreted as being produced by wildfire, but, in addition, the occurrence of char particles provides evidence of the burning of in situ peat (Petersen, 1998). The coals R1 and R2 have a higher inertinite content and may represent drier (raised) environments with ignition started by lightning strikes. These authors (Petersen and Andsbjerg, 1996; Petersen et al., 1998) also document a landward increase in fires and describe the effects of ground fires in particular. This has the effect of burning the peat in situ and lowering the peat surface down to the groundwater table, which may promote the redeposition of inertinite. However, in some coals, there is also indication of crown fires alone in cases where there was a high water table.

It is concluded that there was a high frequency of fires in the mire systems. Further, Petersen and Andsbjerg (1996) state “the somewhat uneven distribution of inertinite in the Bryne Formation Coals is probably to some degree related to the level of the water table (wetness of peat), but investigations of recent mire systems show that

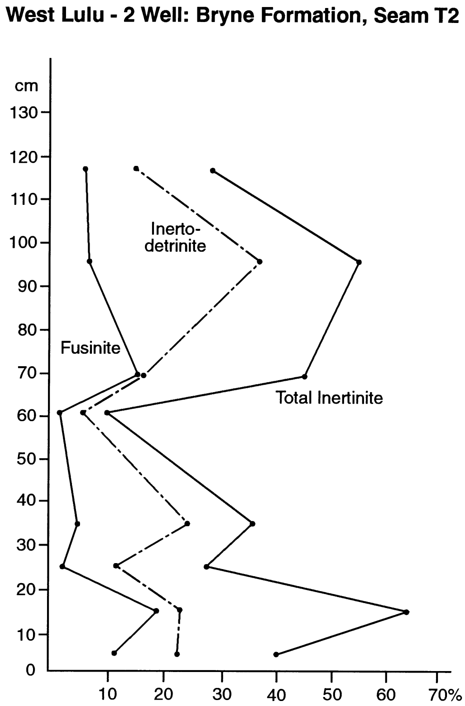


Fig. 23. Inertinite percentages in Seam T2, Bryne Formation, Middle Jurassic, West Lulu 2 Well, North Sea [after Petersen and Andsbjerg (1996)].

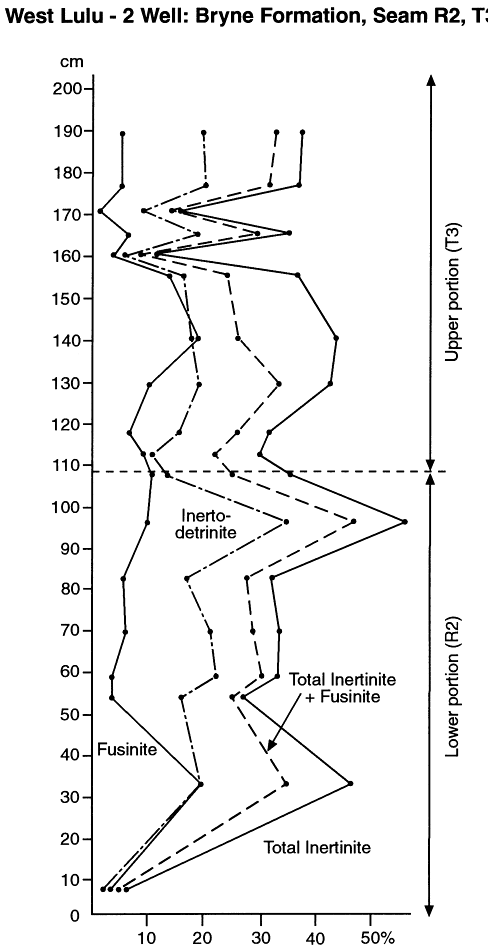


Fig. 24. Inertinite percentages in Seams R2/T3, Bryne Formation, Middle Jurassic, West Lulu 2 Well, North Sea [after Petersen and Andsbjerg (1996)].

wildfires may be related to vegetation (Cohen and Stack, 1996)".

10.3. Late Jurassic of Greenland

In their study of Late Jurassic sediments of northeast Greenland, Bojesen-Koefoed et al. (1997) describe a sequence of lacustrine mudstones with a high intertinite content (30–58 vol.%). This inertinite is mainly inertodetrinite, <10 μm, and is interpreted as being wind blown from hinterland fires and trapped in lakes in a seasonal warm temperate–subtropical humid climate. The inertinites only occur in the lake sediments and not in coeval marine sediments, which is interpreted to mean that the charcoal was only trapped when sedimentation was at a minimum. These authors also measured the inertinite reflectance and found three distinct populations: (1) 1.51–2.06% Ro with average 1.73; (2) a small population, 2.93–3.80% Ro, average 3.39; (3) a larger population 4.65–5.16% Ro, average 4.91. Using experimental data from Jones et al. (1991), they equated the low reflecting population as being charred at 400°C and the highest reflecting population as being charred at over 700°C. These authors conclude "During initial phases of renewed base level rise, shallow, flat-bottomed lakes or lagoons were formed on the coastal plain and acted as traps for fine clastic sediment and predominantly wind borne inertinite, generated by wildfires in the hinterland." (Bojesen-Koefoed et al., 1997).

11. Cretaceous conflagrations

11.1. Wealden fires

Charcoal becomes increasingly important in sediments from the latest Jurassic and early Cretaceous (Koeniguer, 1980). Francis (1984), in her study of latest Jurassic earliest Cretaceous environments and floras of the Purbeck of southern England, noted the importance of fire in coastal conifer forests. She further concluded that the climate was seasonal, the dominant tree being a cheirolepidaceous conifer thought to have been adapted to growing in a semi-arid environment. Francis (1984) also pointed out that the soils underlying the Fossil Forest on the Portland peninsula contain charcoal fragments, yet there appear to be no charred tree stumps or logs. She suggested that the fire past quickly through the undergrowth, charring twigs and shoots. No detailed analysis of the charcoal has yet been published.

The occurrence of fires in the overlying early Cretaceous Purbeck–Wealden has been well documented (Allen, 1998). Alvin (1974) reported siltstone layers, often occurring as gutter casts, with abundant charcoalified *Weichselia* (a fern) (Fig. 25) from the Isle of Wight, England. He also noted rarer remains of the fern *Phlebopteris dunk-*

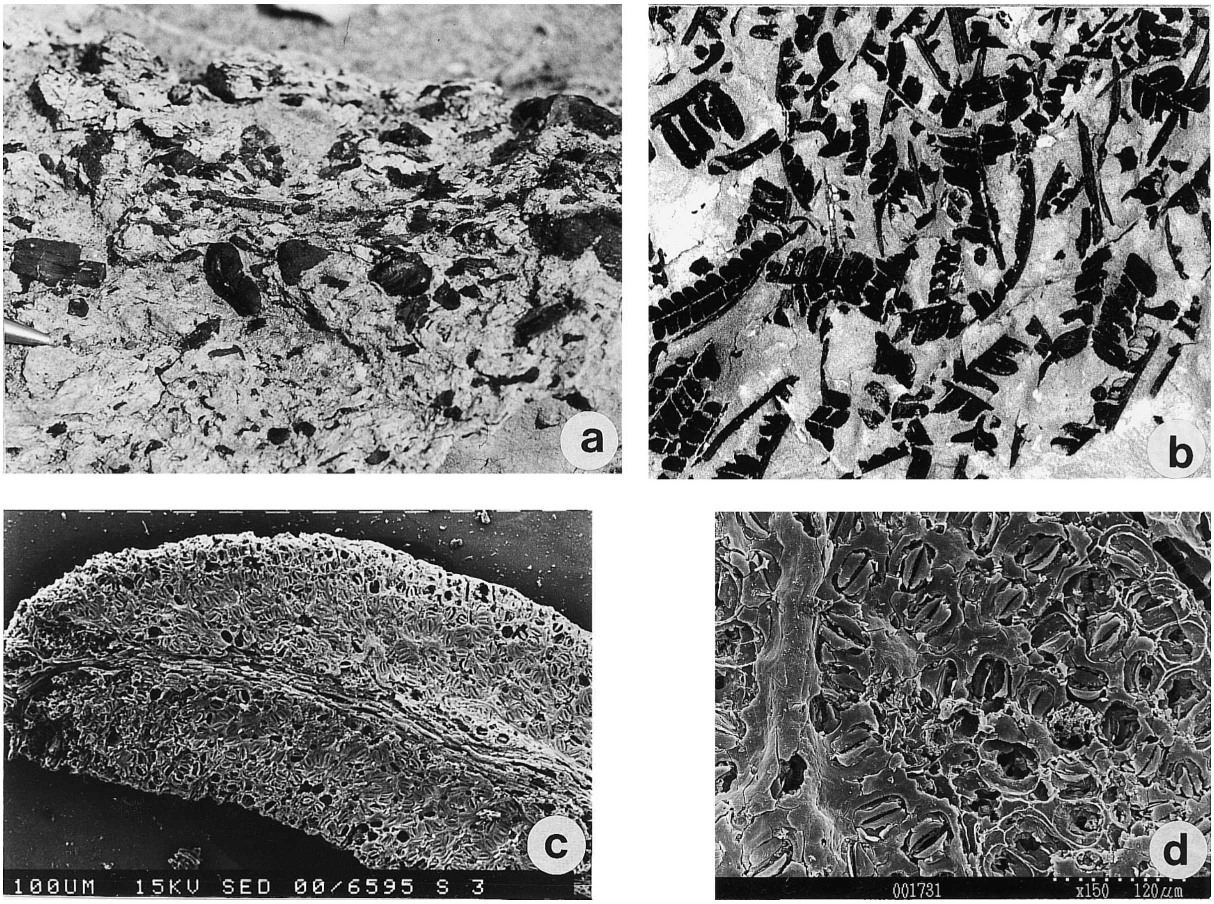


Fig. 25. Charcoal from the Lower Cretaceous Wealden deposits of the Isle of Wight, England. (a) Wood charcoal in sandstone facies (Bed 3, Fig. 26). SU422817 (scale 1 cm). (b) Charcoal of the fern *Weichselia* from siltstone facies (Bed 25, Fig. 24) SU446797 (×1). (c), (d) Scanning electron micrographs of isolated charred pinnules of *Weichselia* showing: (c) overall morphology (×40), (d) detail of stomata (×100).

eri. Most of the plants were charred. Alvin (1974) concluded that the fern dominated this community in which it grew and when subjected to desiccation was especially vulnerable to the spread of fire.

Harris (1981) further noted the more widespread occurrence of charred ferns in the English Wealden and drew attention to the charred ferns in the Polish Lower Cretaceous (Reymanówna, 1965). Harris described material from the Weald Clay at Beare Green Brick Pit near Holmwood, Surrey, England. A quantitative analysis of one block showed that *Weichselia* with pinnules is the most abundant charred fern. Other fern pinnules, however, are common, including *Gleichenites* and *Phlebopteris*. The fragments are small, but they show little evidence of being worn by water transport. The fern charcoal lies on bedding surfaces of fine siltstone. Similar material was reported by Harris (1981) from several other localities in the Weald. The deposits are all non-marine (Allen, 1998), but charred *Weichselia* is also known from marine deposits overlying the Wealden in the Isle of Wight (Harris, 1981, personal observation). Harris (1981) suggested that the ferns lived on low banks by the floodplain. He argued that there were no gymnospermous trees. The three fern species were interpreted as being tall herbs and made an analogy with bracken-covered heath of today (Harris, 1981). This may not be supported by modern taphonomic studies (Scott et al., 2000a). Harris (1981, p. 56) conjectured: "In the wet season the herbaceous ferns flourished. As it dried they produced and dispersed their spores and finally the leaves withered, just as grass savannah does today. I imagine, but without evidence, that the wet season began with high winds and electric storms and if dry, a lightning strike preceded the first heavy rain it would start a fire, as it does today, and the fire would spread widely. Then heavy rain would wash down ashes and charcoal, and some of the bits of charcoal, carried as a bottom load, would be left in last year's scour basins". Harris (1981) also concluded that these charcoal deposits may have given an unrepresentative picture of the vegetation and noted some of the taphonomic problems. Many more plants have been found preserved as charcoal in the Wealden (Watson and Alvin, 1996). Alvin et al. (1981) described charcoalified wood of several conifers, including *Pseudofrenelopsis* from the Wealden of the Isle of Wight.

In their study of charcoal assemblages of the Wealden of the Isle of Wight, Collinson et al. (2000) report two distinctive assemblages. At Hanover Point they describe a charred wood-dominated assemblage from the Wessex formation mudstones and at Shepherds Chine they describe a charred fern-dominated assemblage from the overlying Vectis Formation siltstones. They interpret the plant debris associations as representing low diversity fire-prone vegetation: Hanover Point a flood-plain conifer forest community and

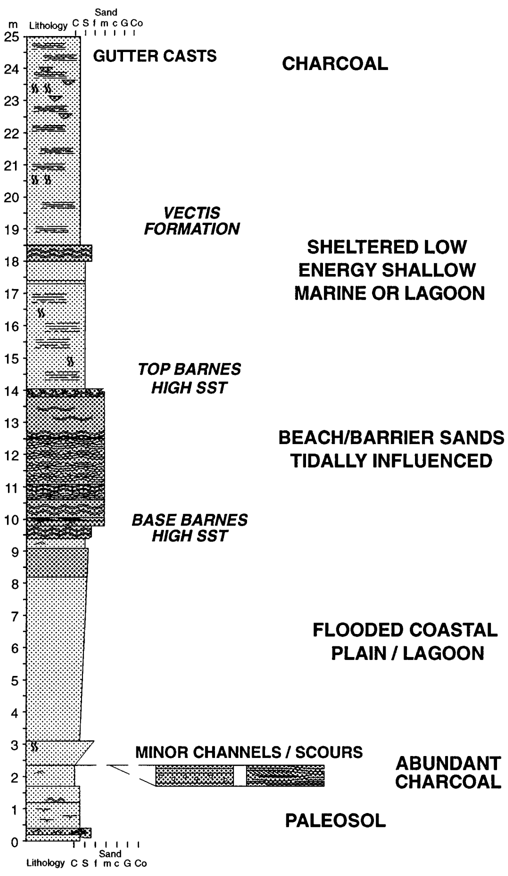


Fig. 26. Sedimentary sequence of the Vectis Formation, Lower Cretaceous, near Shepherd's Chine, NGR SV422817, Isle of Wight, England, showing the position of charcoal horizons shown in Fig. 23.

Shepherds Chine specialist coastal fern and conifer communities. Overall, the fern association has been interpreted by Collinson (1996) as 'savanna' and/or prairie on a fire-prone coastal floodplain (Watson and Alvin, 1996).

There are several horizons with charcoal in the Vectis Formation near Shepherd's Chine (Collinson et al., in preparation) (Fig. 26). A sandy unit at the base is dominated by gymnospermous wood charcoal (Fig. 25a), whereas siltstone horizons and gutter casts higher up are dominated by fern charcoal (Fig. 25b). Although the interpretation of these assemblages is as two different fire-prone communities, it is nevertheless possible that taphonomic processes may have separated predominantly leaf from wood charcoal, owing to their different hydrodynamic properties (Nichols et al., 2000; Scott et al., 2000a). More data are needed.

Charcoal assemblages have also been reported from the early Cretaceous of Nova Scotia (Calder et al. 1998; Scott et al. 1998). Several thick charcoal-rich units occur within kaolin clay deposits in the Shubenacadie and Musquodoboid basins. Some of the horizons extend over 10 km. The charcoals include both gymnospermous wood and fern rachises and pinnules (Fig. 27) and resemble those in the Wealden deposits referred to above.

Other charred ferns have been described from shallow marine deposits of Lower Cretaceous age in Bedfordshire, England (Herendeen and Skog, 1998). The morphological characters of *Gleichenia chaloneri* are interpreted as indicating an arid environment with periodic fires.

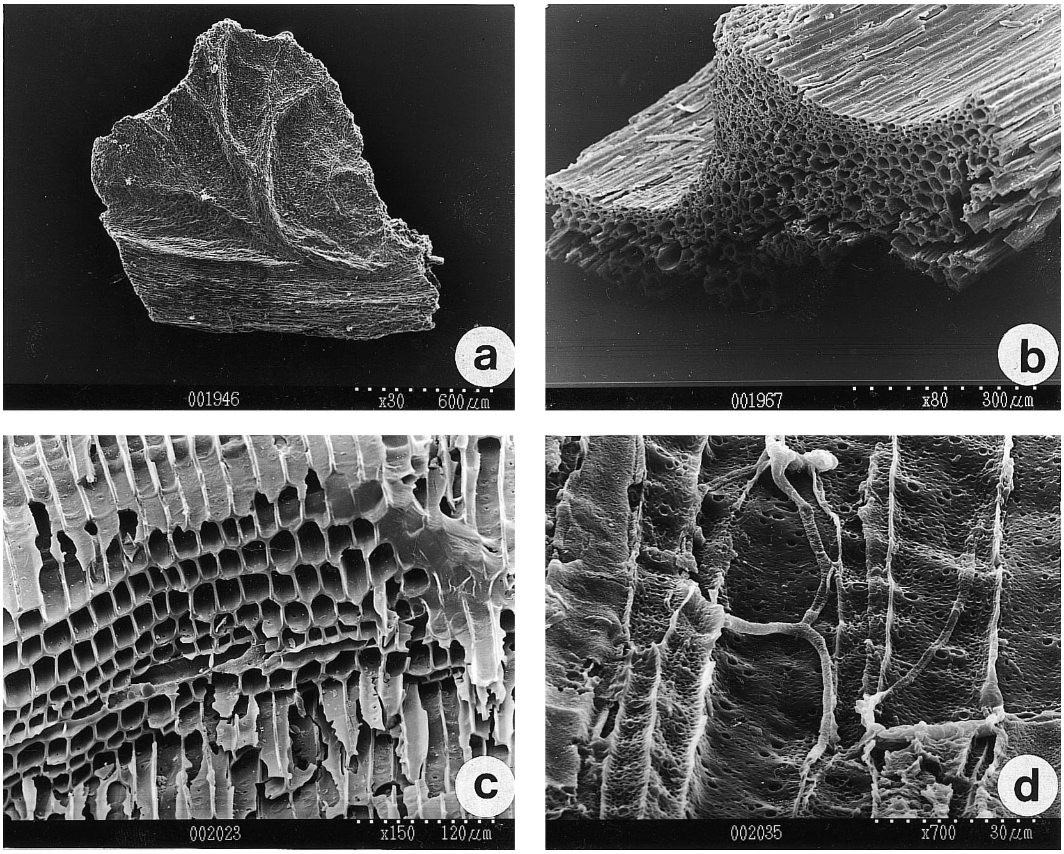


Fig. 27. Scanning electron micrographs of charcoal from the Lower Cretaceous of Nova Scotia, Canada. (a) Detail of fern pinnule. (b) Fern rachis. (c) Conifer wood. (d) Fungally infected conifer wood.

Fusain has been widely reported from Lower Cretaceous coals (e.g. Kalkreuth et al., 1991). Coal seams in the mid-Albian Gates Formation of British Columbia, Canada, contain common fusain. Kalkreuth et al. (1991) have shown that the inertinite content of the coals is generally around 20%, but that it reaches 40% at some horizons (Fig. 28). Lamberson et al. (1996) concluded that there were long periods of dry or periodically dry, forested fresh water swamps. Fire was probably an integral part of such an ecosystem, as in some *Taxodium* swamps today (Komarek, 1973).

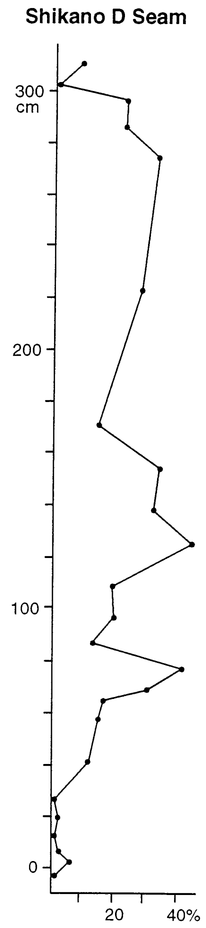


Fig. 28. Inertinite distribution in the Shikano D Coal Seam, Gates Formation (Albian, Lower Cretaceous), Alberta, Canada [after Kalkreuth et al. (1991)].

11.2. Mid-Late Cretaceous fires in Sweden and the USA

Abundant small flowers preserved as charcoal in the late Cretaceous of Sweden have been described by Friis and co-workers (Friis and Skarby, 1981, 1982; Friis 1983, 1990; Friis et al., 1988) (Fig. 29). The interest in early flowers led to a search for additional material and the discovery of several sites yielding diverse charcoal assemblages (Friis et al., 1986). Although there are no detailed descriptions of the deposits or their total floral composition, some general comments can be made. A diversity of flowers is reported and wood occurs at the same sites (Friis, 1990). The flowers came from kaolin-rich sediments exposed at Åsen in Scania in north-east Sweden (Friis and Skarby, 1981, 1982; Friis, 1985a,b,c, 1990; Friis et al., 1986, 1988; Crane et al., 1989). They were associated with other plant remains in fluvial, cross-bedded, poorly sorted sands and were apparently transported as bedload (Friis and Skarby, 1981; Friis, 1990). Fruits and seeds, as well as conifer leaves, are common. The angiosperm remains are preserved as charcoal (Friis, 1990), but no comment is made on the preservation of individual organs or on the thickness of the charcoal-bearing horizon. Friis (1985c) interprets the assemblage as litter that was charred by ground fire before transport and incorporation into the sediment. The flowers are around 2 mm long and 1 mm broad (Friis, 1985a,b) and in the same size category as recent charred heather flowers, but taxonomically quite different (Fig. 29). Scott et al. (2000a) describe the concentration of flowers of this size by wind and this may have occurred before the resultant concentrate was washed into a water body. The association of a variety of plant species and organs suggests rather minimal transport.

Similar charcoalified plant assemblages are also known from sites in North America (Crane et al., 1989; Drinnan et al., 1990; Crane and Herendeen, 1996) and Europe (Portugal; Friis et al., 1994b), suggesting an intimate relationship between early angiosperms and fire. The assemblages range in age through the mid Cretaceous (Albian) of Maryland (Friis et al., 1988; Drinnan et al., 1990, 1991; Herendeen, 1991), and Virginia (Friis et al.,

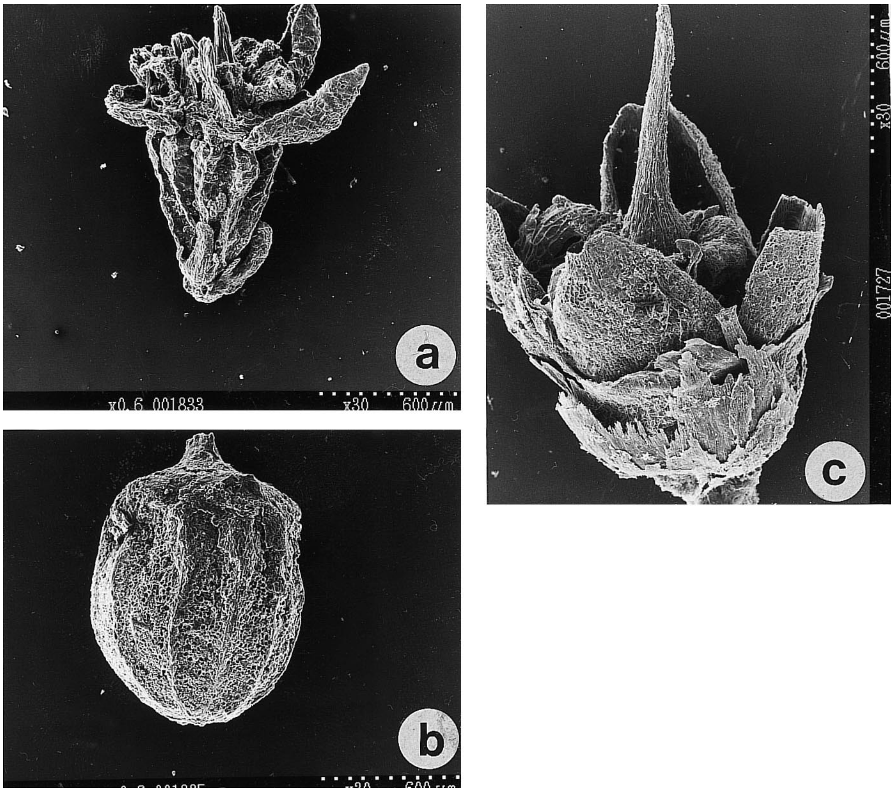


Fig. 29. Cretaceous and Recent charred flowers. (a), (b) From the Scania Formation, Upper Cretaceous, Sweden: (a) *Scanianthus*, (b) *Antiquocarya*. (c) Recent *Calluna* flower from Frensham, Surrey. NGR SU49051415.

1986, 1994; Crane et al., 1993, 1994) through the Cenomanian of Maryland (Drinnan et al., 1991), the Turonian of New Jersey (Crepet et al., 1992; Herendeen et al., 1994), the Santonian of Georgia (Herendeen et al., 1995, 1999; Magallón-Puebla et al., 1996; Sims et al., 1998) to the Santonian–Campanian of North Carolina (Friis, 1985a,b; Friis et al., 1998; Crane et al., 1986).

12. Fires at the K–T boundary

Recent evidence suggests the occurrence of a major meteorite impact at the Cretaceous–Tertiary boundary (Alvarez, 1987). Although there has been significant interest in the effects that this might have had upon the physical environment (e.g. tsunamis, earthquakes, atmospheric chemistry — Kruge et al., 1994, 1996; Smit et al., 1994; Jones, 1996; Arinobou et al., 1999), much debate has surrounded the extinction of the dinosaurs (Alvarez et al., 1980; MacLeod et al., 1997).

The effects of the postulated impact upon the terrestrial vegetation have been debated by numerous authors (Saito et al., 1986 and references cited therein) and much attention has been focused upon the supposed occurrence of wildfires at the boundary and their effects upon the extinction of terrestrial biota (Argyle, 1986; Wolbach et al., 1985, 1988, 1990b). However, studies of coal sequences have yielded no evidence for exceptional fires at or about this time (Sweet and Cameron, 1991; Scott et al., 2000b).

12.1. The fossil evidence

Wildfires produce two predominant types of material from the burning of vegetation: charcoal,

the particles of which may range in size from a few micrometres upwards and may be wind or water borne (Clark, 1988; Nichols et al., 2000), and soot, black or 'elemental' carbon (Jones et al., 1997). Although much of the evidence for fire in the fossil record comes from macroscopic charcoal, there is increasing interest in the distribution of black carbon in the marine record (Lim and Cachier, 1996; Bird, 1997). Smith et al. (1973) showed that a record of fires could be obtained by analysing marine sediments for elemental carbon. Griffin and Goldberg (1979) discussed the recognition of microscopic particles and Herring (1985) provided data on the charcoal flux into the Pacific by documenting a Cenozoic record of burning. We have no data, however, on the marine record of elemental carbon for interpreting pre-Cretaceous fires. Some authors (e.g. Arinobou et al., 1999) have used PAH data to identify ancient fires (Killops and Massoud, 1992), but in the case of Korean Jurassic these chemical markers were associated with fossil charcoal (Massoud et al., 1993).

12.2. Global or local fire?

Wolbach et al. (1985) described K–T boundary claystones from marine sections from New Zealand, Spain and Russia for enrichment in elemental carbon, which they regarded as evidence for a global fire (Wolbach et al., 1985, 1988, 1990a,b, 1998). More recently, isotopic data have been claimed to support this interpretation (Wolbach et al., 1988; Ivany and Salawitch, 1993; Arinobu et al., 1999). Wolbach et al. (1985, 1988, 1990a,b) suggest that there was a 10^2–10^4-fold enrichment of uniformly isotopic carbon in the boundary layer. These authors' material from up to 40 cm below the boundary provide no data showing that the levels were exceptional compared with other parts of the geological column.

Boundary claystones in terrestrial sequences appear not to be associated with large quantities of macroscopic charcoal. This might have been expected if there was a truly global wildfire. Wolbach et al. (1990a,b) used the occurrence of inertinite in coals above the K–T boundary (Tschudy et al., 1984) to support their hypothesis of a global fire. Inertinite distribution in mid-Cretaceous coals (Lamberson et al., 1996) suggests, however, that fires were a normal part of mire ecosystems in the Cretaceous. Similarly, inertinite distribution in coals across the K–T boundary in North America do not favour an exceptional fire or fires at that time (Sweet and Cameron, 1991; Scott et al. 2000b).

Evidence for a global fire at the K–T boundary is not proven anywhere [see also Jones (1996)]. If truly global it would have affected most vegetated areas, especially those with thick accumulations of fuel load. One might expect that intense burning of vegetated upland areas would have led to increased erosion and deposition into lowland sites. For this we have no evidence. Moreover, besides 'soot' in oceanic sediments we would have expected charcoal deposits in near-shore marine deposits, concentrates of charcoal in channel sandstones and fusain bands at the boundary — even evidence of burnt peat surfaces.

Two possible explanations of the contradictory data are as follows.

1. Regional fires broke out at the Cretaceous–Tertiary boundary but were linked to the normal fire cycle regime rather than a bolide impact. Background fire data from Cretaceous marine sediments are admittedly poor, but evidence from the macrofossil record suggests that wildfires were a regular part of many terrestrial ecosystems.
2. A regional but not global fire at the boundary was ignited by the impact but is not reflected in the terrestrial record in North America.

On current balance the first explanation seems more likely.

13. Tertiary fire

There has been less discussion of fire during the Tertiary. Herring (1985) documents an increase in fire records through the Tertiary, but bases this only on elemental carbon records from the Pacific region. Many workers believe that fires were less important in some Tertiary environments because fusain levels in Tertiary coals are low (Taylor et al., 1998). Shearer et al. (1995) document the percentage of 'carbonised' plant material in coals through

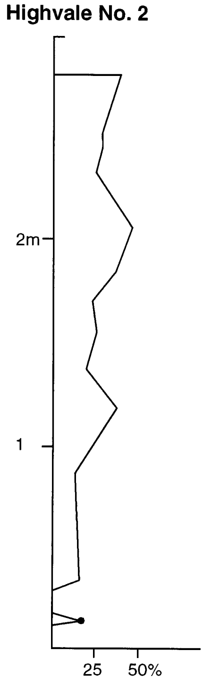


Fig. 30. Inertinite distribution in the Palaeocene Highvale No.2 Coal, Alberta, Canada [after Demchuk and Strobl (1989)].

the Tertiary and point out that a large proportion have less than 5%. As seen, data from whole coals may be misleading and there is little on fires in Tertiary mire sequences. Given the abundance of records of charred flowers in the Cretaceous, it is puzzling that there seem to be no records of charred flowers from the Tertiary, especially as large numbers of fruits and seeds have been collected and studied. Perhaps little fire-prone vegetation has been sampled or there were fewer fires.

13.1. Scarcity of early Tertiary records

Most of the data on Palaeocene–Eocene charcoal come from coal sequences. There appears to be no systematic study of Tertiary charcoalified plants. Inertinite levels in coals of this age may range between at 8 and 29% (Shearer et al., 1995). Evidence for fires has been reported from Eocene coals (Demchuk, 1993) (Fig. 30), but few publications discuss inertinite distribution directly in terms of frequency. Collinson (oral communication, 1999) is currently investigating the Chobham Lignite in Kent, England, (approximately Palaeocene–Eocene boundary) and has found numerous charcoal horizons within the 2 m thick lignite.

Gentzis and Goodarzi (1990) record relatively low levels of inertinite (usually around 10%) in late Palaeocene coals of Canada. Some horizons (e.g. Obed-Marsh Seam 1, section 2, unit B) may contain more than 5%. Such units are overlain by clastic deposits and this may be a fire splay (Cohen, 1974). Gentzis and Goodarzi (1990) also report a predominance of fusinite over semifusinite, indicating high-temperature fires. In the Poplar River Mire Coal, Potter et al. (1991a,b) record >20% inertinite, with peaks up to 30% (Fig. 31). They found up to 10% inertodetrinite in the coals. Likewise, the Highvale No. 2 coal usually contains over 25% inertinite with peaks up to 50% (Demchuk and Strobl, 1989) (Fig. 30). Contrasting with these North American Palaeocene coals, Eocene coals from New Zealand (Newman et al., 1997) have low inertinite contents (generally less than 5%), but with rare peaks of >5% (Fig. 32). Low inertinite contents are also reported from Palaeocene and Eocene coals in North America.

13.2. Miocene brown coals

Fusain occurs in Miocene brown coals, from Germany, Australia and elsewhere, but the records mainly concern a few thin bands rather than continuous backgrounds (Taylor et al., 1998). Some of the charcoal layers undoubtedly represent fire events, and the flora may change across the horizon in question (Grebe, 1953). The published charcoal contents of Miocene and later coals are generally low (<5%) (Shearer et al., 1995) and may reflect a real decrease in fire frequency in mire ecosystems. If this is genuine, then climatic and atmospheric causes may be involved. There are no published data on the distribution of macroscopic charcoal in the Northern Hemisphere Miocene sediments, though it does occur in the coals and clastic sediments of the early Miocene deposits of the Oberdorf Mine, Austria (Hass et al., 1998; Scott, personal observation). In the early to middle

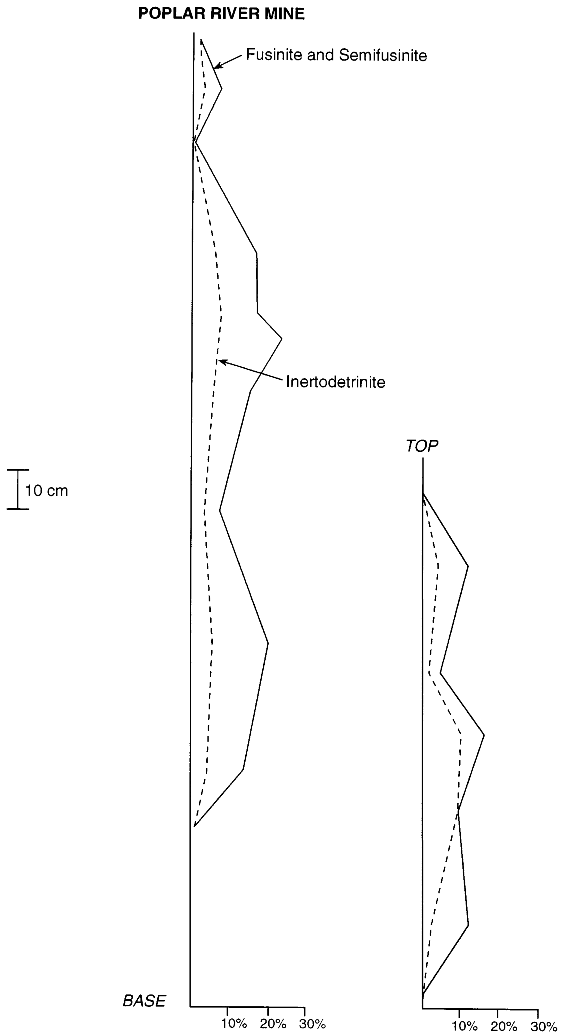


Fig. 31. Inertinite distribution in the Palaeocene Poplar River Mine Coal, Saskatchewan, Canada [after Potter et al. (1991a,b)].

Miocene Yallourn Formation brown coals of Victoria, Australia, there are horizons that contain charcoalified pinnules of the fern *Gleichenia*, which is very similar to *Gleichenia dicarpa*, a modern fire-tolerant species (Blackburn and Sluiter, 1994; Collinson, 1996).

13.3. Absence of later records

Absence of charcoal from later Tertiary sequences may be real or indicate a lack of study.

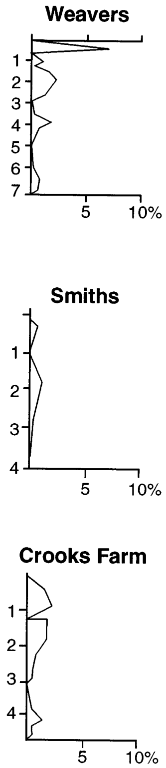


Fig. 32. Inertinite distribution in Eocene coals from the Waikao Coal Measures, New Zealand [after Newman et al. (1997)].

The author has noted charcoal in coals and clastic sediments in the Pliocene of Italy (Fig. 33), but such deposits have been little studied. It is possible that there was a general decrease in 'natural' fire frequency through the late Tertiary and that the sudden rise in charcoal records in the late Quaternary was related to human firing (Moore, 2000). More data are required, including negative data, before low charcoal records can be explained.

14. Conclusions

Fires are an integral part of many of the world's ecosystems today. Most natural wildfires are started by lightning strikes. The available fuel may be part of the living vegetation or in the litter or soil layers. Surface fires burn the accumulated litter and smaller living plants; ground fires burn the organic-rich soil layers, and crown fires burn the

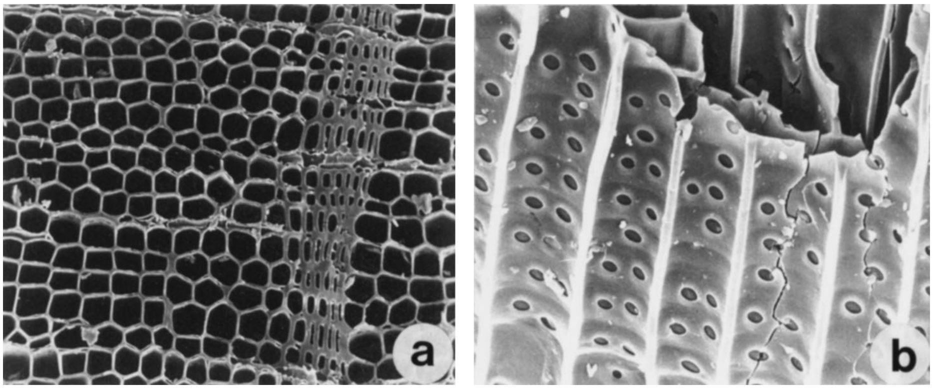


Fig. 33. Scanning electron micrographs of *Glyptostobus* conifer charcoal, Pliocene, N. Italy. (a) Tangential section showing growth ring (×40). (b) Longitudinal section showing pitting in tracheid walls (×200).

crowns of living trees. Temperatures in many ground fires range between 300 and 600°C, with about 400°C being common. Crown fires are hotter, often 800–900°C. Much of their leaf and fine twig material is consumed and most of the charcoal produced is from larger branches and incompletely consumed trunks. Most surface fires generate quantities of charcoal that are not moved by convective currents during the fire. Crown fires, on the other hand, can give rise to small charcoal particles susceptible to wind dispersal.

Charcoal often shows excellent preservation of anatomical features. Significant changes take place in its morphology with increasing temperature. Cell walls first homogenise, then break up and disintegrate. Reflectance studies of polished surfaces show increasing reflectance with increasing temperature. Most low-temperature fires produce charcoals with reflectance values less than 2% (semifusinite). In contrast, high-temperature fires, such as most crown fires, produce higher reflecting charcoals either as large fragments (fusinite) or small particles (inertodetrinite).

Settling and flume tank experiments show that settling rate is affected by the charring temperature, plant species, plant organ and freshness of the plant material. Most larger charcoal particles will be water transported and incorporation into the bedload is favoured by moderate current velocities.

Under modern conditions, enhanced erosion and sediment transport may result from where ground is bared by an intense fire. Plant communities may recover or change after a fire. Many of today's fire systems appear to have evolved over a considerable period of time.

The fossil record of Pre-Quaternary and non-anthropogenic fire is based mainly on the occurrence of macroscopic charcoal (fusain). This has been shown to yield excellent anatomical structure and high reflectance. A wide range of plant organs are preserved as fusain. The earliest records come from the Devonian, but extensive fusain deposits did not appear until the early Carboniferous when widespread wildfires clearly began. This may be due to an increased oxygen concentration in the atmosphere, particularly in the Euramerican tropical zone.

Fusain assemblages are found throughout the rest of the Phanerozoic, indicating a more or less continuous record of fire. The hypothesis of a global wildfire at the Cretaceous–Tertiary boundary started by a meteorite impact must be treated with caution.

Combination of morphological and reflectance data can be used to interpret fire type and intensity. Pre-Quaternary fires apparently had profound effects on some erosion–depositional systems and a wide variety of ecosystems. The widespread and frequent occurrence of wildfires through a long period of time must be taken into account by those reconstructing past environments and those attempting to unravel the nature of our present terrestrial ecosystems.

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